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AGGREGATION CHARACTERISTICS AND MATURITY OF PEAK DISTRICT SOILS

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Abstract

Soil aggregation and aggregate stability are fundamental factors in determination of soil erodibility. The aggregation characteristics of soils in a region of high erosion potential are measured, and controlling factors examined. A relationship between increasing soil maturity and decreasing aggregate stability is described, and its significance in relation to Penck's *Aufbereitung* concept is discussed.

INTRODUCTION

The Peak District of Derbyshire is an upland region of highly accidented relief which has a considerable potential for serious soil erosion damage. The fact that such damage is not already widespread may be attributed primarily to the maintenance of a permanent vegetation cover, except in very localised areas. While the vegetation cover is still largely intact, incidence of removal has increased as a result of overgrazing, turf slumping and accidental burning. The third cause, in particular, is increasing in importance because of the increased access for tourists to moorland areas. In an attempt to assess the potential for serious damage by surface wash as a result of destruction of the vegetation cover, an experimental study was carried out over a period of three years (Bryan, 1969a). During this study it appeared that the fundamental factor controlling the resistance offered to erosional processes by the soil is the stability of soil aggregates. Accordingly the study on which this paper is based was carried out, to determine the characteristics of soil aggregation and the controlling variables.

While the importance of aggregation characteristics in determining the effectiveness of erosional processes had been recognised, the wider significance of some of the results was not fully appreciated until the appearance of Beckett's (1968) restatement of Penck's (1924, 1953) *Aufbereitung* concept in pedological terms. Fundamental to this concept is the theoretical assumption that soil detachability is a function of soil maturity. Beckett (1968) has assembled a considerable amount of theoretical support for this assumption, and quantitative laboratory data obtained in this study provides further strong support.

ANALYSES OF AGGREGATION CHARACTERISTICS

The soil samples used in this study were collected from 36 profile pits, representative of the range of soil development in the Peak District, which has been described elsewhere (Bryan, 1967a). Samples were cut from the profiles with a sharp knife, carried to the laboratory in crush-proof containers, and air-dried for ten days prior to analyses. Both aggregate size distribution and aggregate stability were determined by a wet-sieving technique, as critically reviewed by Russell (1949), and Kemper and Chepil (1965). The instrument used in wet-sieve analyses (Bryan, 1968a) was based on the original instrument developed by Yoder (1936). It provided separation at four apertures, 3 mm., 2 mm., 1 mm., and 0.5 mm., respectively. The number of sieves was a compromise between the requirements of aggregate stability analysis which would ideally involve only two sieves, and aggregate size distribution analysis, which would ideally require six sieves.

In aggregate analyses the initial moisture content of the samples is critical. In this study the rapid immersion technique was used, which has been shown to be the most destructive to aggregates (Emerson, 1954), and which some workers (Williams et al., 1966) believe to be essential in wet-sieve analyses. The technique is also believed to bear the closest resemblance to wetting of soils under natural conditions (Low, 1954, Clement and Williams, 1959) and was therefore particularly suitable for this study. The laboratory procedures followed have been described in detail in a previous paper (Bryan, 1968a).

Aggregate size distribution

Results of aggregate size distribution analyses, classified for convenience into generalised parent material groups ,are shown in Figs. 1 to 4. The aggregates represented are water-stable to the process of slaking (Yoder, 1936), although not necessarily to that of raindrop dispersion. There is no recognised "standard" aggregate size distribution, but the pattern shown by most "limestone" soils (Fig. 1) appears to be characteristic of stable, well-aggregated freely-drained soils. The distribution shows double maxima, the higher peak being in the >3 mm. diameter category. Amongst the "limestone" soils only samples from profile 36 depart markedly from this pattern, samples from the A_2 and B_2 horizons showing an aggregation pattern which is apparently typical of all soils of unstable aggregation, regardless of parent material. Profile 36 is an atypical soil being derived, at least in part, from a thin deposit of cherty gravels overlying the Carboniferous Limestone, and is of much coarser texture than the other "limestone" soils. It is atypical also in the rapid decline in aggregation with depth below the surface, most "limestone" soils showing little change, or actual improvement. This anomaly is explicable both by distribution of humus within the soil, and by rooting patterns.

The "gritstone" soils (Fig. 2) are more varied in their pedogenic environments, and aggregate size distributions show corresponding wide variations. In general aggregation is not as well-developed as in the "limestone" soils, and many soils show a marked structural deterioration with depth below the surface. This

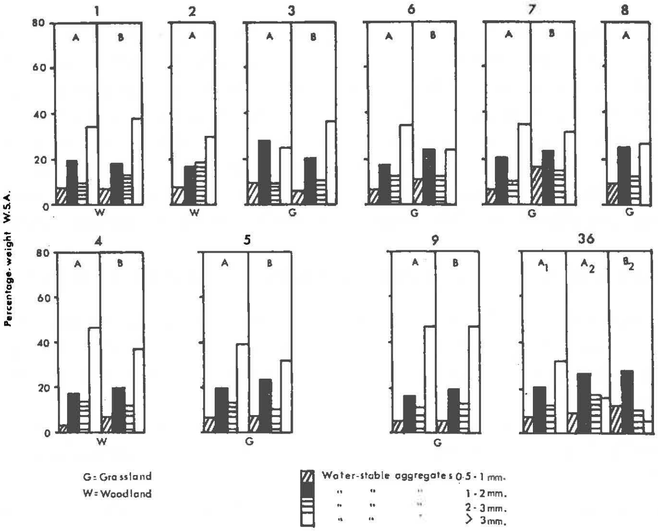
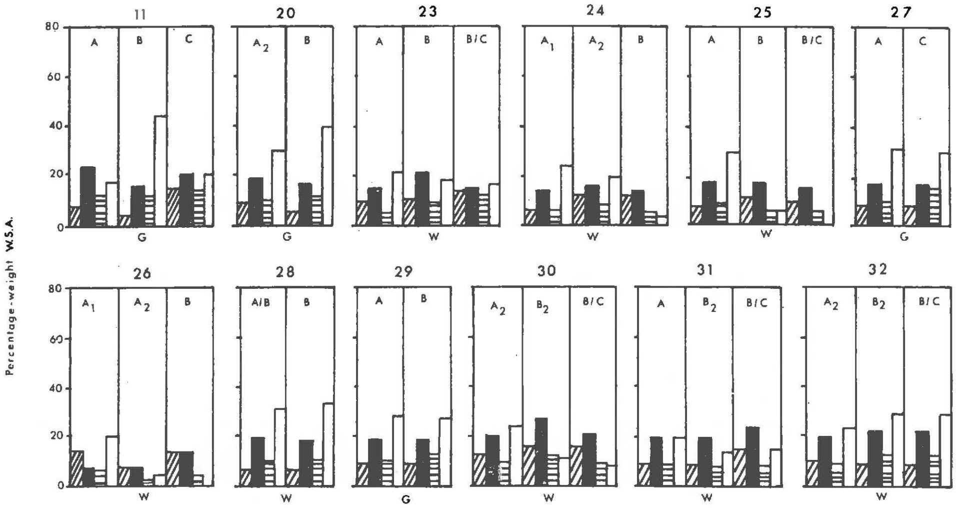
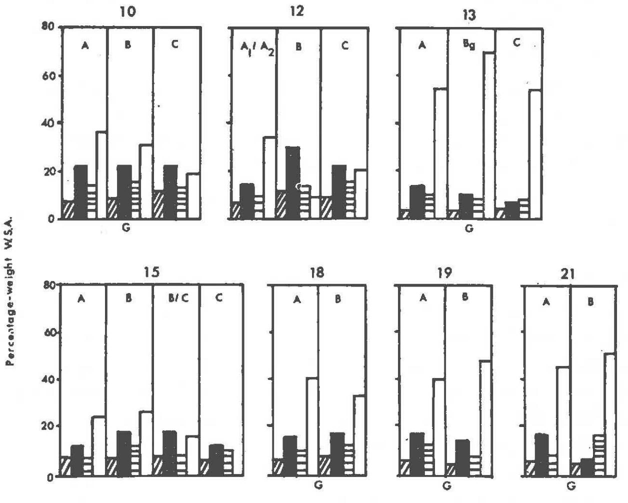


Figure 1. Aggregate size distribution in soils developed over limestone parent materials.



Key as in Fig.1

Figure 2. Aggregate size distribution in soils developed over gritstone parent materials.



Key as in Fig.1

Figure 3. Aggregate size distribution in soils developed over shale parent materials.

apparently reflects primarily the distribution of humus within the soil. Where humus is rigidly segregated into surface horizons deterioration is rapid, unless the decline in humus content is compensated for by increase in other aggregating material.

Soils developed over shale parent materials (Fig. 3) show very variable aggregate size distributions, reflecting particularly the variability of parent materials. These are in all cases very fine-grained, but in some profiles, such as profile 15, there appears to have been addition of a certain amount of coarse material by creep from sandstone outcrops juxtaposed upslope. This has affected aggregation particularly in the lower horizons where the pattern is conspicuously less stable than that in other "shale" soils. A number of profiles, such as profiles

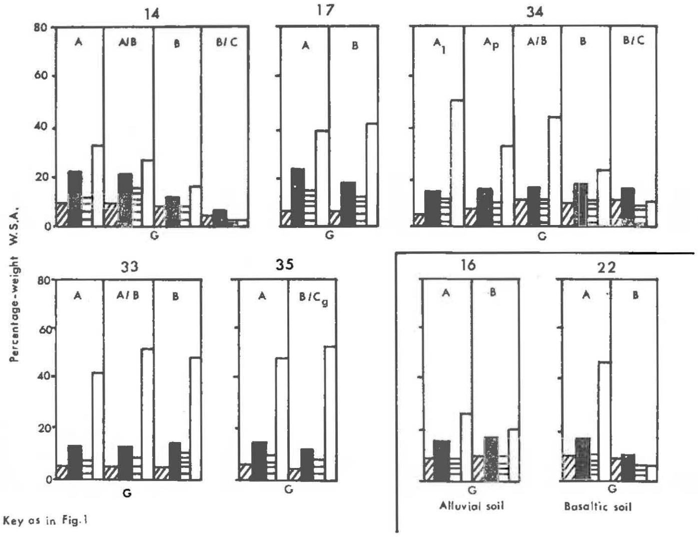


Figure 4. Aggregate size distribution in soils developed over solifluction gravels.

19 and 21, show quite a marked improvement in aggregation with increase in depth. This is probably associated with sesquioxide enrichment in profile 19 and clay enrichment in profile 21.

Most of the samples shown in Fig. 4 are from soils developed over material mapped by the Geological Survey as "solifluction gravels." This material is extremely variable in mechanical composition, ranging from almost pure gravel to heavy loam. This variability is reflected in the aggregation characteristics, particularly of the lower horizons, as in profiles 14 and 33. The number of samples involved is too small to make valid generalizations about these soils.

Aggregate stability

Histograms showing aggregate size distribution give an indication of aggregate stability, but for most purposes it is desirable to isolate a definite index of aggregate stability. A very large number of indices of aggregate stability have been proposed and used by various workers with varying degrees of success (Conaway and Strickling, 1962). The most generally satisfactory index appears to be the recording of percentage-weights of water-stable aggregates larger than a given diameter. The most widely-used indices have been percentage-weights >2 mm. and >0.5 mm. diameter. Variations in these parameters for the 90 samples analyzed have been plotted in Fig. 5. Both indices show the same general pattern, but the sensitivity of the percentage-weight >2 mm., as measured by the amplitude of the plotted line, is higher. Use of this index is therefore preferable, particularly as the addition of all fractions >0.5 mm. could obscure important variations in the larger aggregate categories. As the bulk of the aggregates >2 mm. are also >3 mm., (Figs 1-4), the percentage-weight >3 mm. should be even more sensitive as an index. Mean values of these three indices of aggregate stability, together with values for loss-of-weight on slaking, are shown for different sample sub-groupings in Table 1.

All the indices based on size retention show the same general pattern of distribution between groups, except for the "limestone" and "shale" groups. If intervals between groups are used as criteria of efficiency, then the percentage-weight >2 mm. is marginally most efficient, and percentage-weight >0.5 mm. generally least efficient. As shown in another study (Bryan, 1968b), however, percentage-weight >2 mm. does not always reflect erodibility accurately, and

Table 1. Mean values of the three different indices of aggregate stability for different sub-groupings of the sample soils are shown below:

Sample Sub-group	>3 mm.%	>2 mm.%	>0.5 mm.%	Slaking loss
Limestone parent material	32.8	44.34	71.73	11.36
	σ 10	σ 10	σ 6	σ 5
Shale parent material	35.02	45.72	67.86	11.37
	σ 17	σ 17	σ 14	σ 19
Gritstone parent material	24.91	34.20	59.63	17.95
	σ 13	σ 15	σ 14	σ 13
Grassland soils	34.74	45.50	68.45	16.29
	σ 13	σ 13	σ 13	σ 12
Woodland soils	21.02	29.92	58.00	16.58
	σ 12	σ 14	σ 14	σ 10
Brown earths	31.19	41.66	64.58	16.90
	σ 13	σ 15	σ 12	σ 14
Podzolic soils	22.21	31.85	56.83	14.52
	σ 12	σ 13	σ 13	σ 12

therefore use of the percentage-weight >3 mm. was preferred for this study. The fourth index shown in Table 1, the loss-of-weight on slaking, reproduces the same pattern of separation as the other indices, except for the vegetation group, but the degree of separation is smaller, and the index therefore less efficient. Comparison of the four indices of aggregation allows the sample sub-groups to be ranked in order of aggregate stability. Aggregates in soils developed over limestone and shale parent materials have comparable stability, and cannot be clearly separated by the indices, but aggregation of "gritstone" soils is clearly less stable, maxima in the >3 mm. category (Fig. 1) are not very high. This reflects the general tendency for calcareous soils to develop crumb structure. Although calcium salts have a flocculating effect on textural separates, and therefore tend to promote aggregation, they actually have a slightly disruptive effect on large aggregates (Peele et al., 1938, Emerson and Dettman, 1960). Amongst the other sample sub-groups, the three most efficient indices show the aggregates of woodland soils to be clearly less stable than those of grassland soils, and all indices show podzolic soils to have less stable aggregation than brown earths.

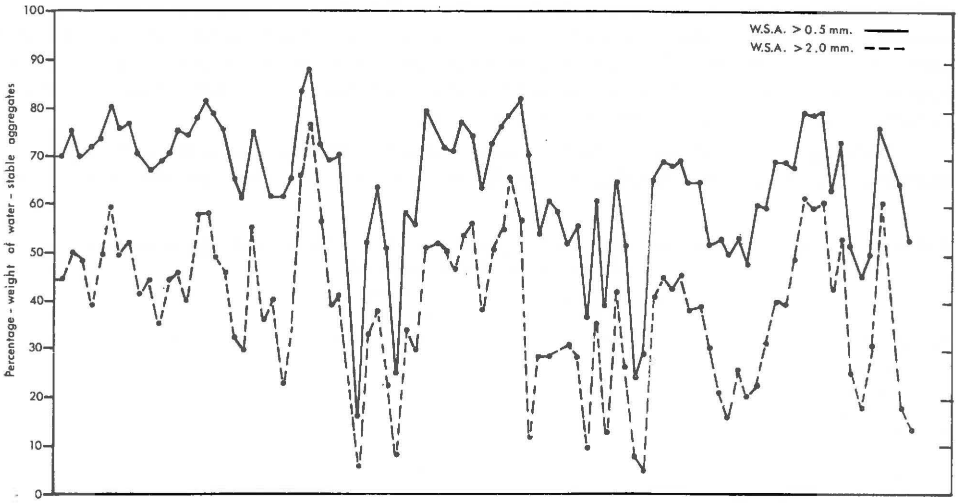


Figure 5. Relative efficiency of different indices of aggregate stability.

Factors controlling variations in aggregate stability

Although the mechanism of aggregate formation and stabilization is not yet understood in its entirety, all evidence points to the existence of a two-stage process (Baver, 1956), which involves movement of textural separates into juxtaposition, and their subsequent cementation to form stable aggregates. Any mechanism which causes movement of separates into juxtaposition may promote aggregation, but cannot, by itself, stabilize aggregates (Rogowski and Kirkham, 1962). Amongst these mechanisms, freeze-thaw cycles, wetting-drying cycles, mechanical compaction and the flocculating effect of calcium salts are the most widely recognized.

Cementation of unstable aggregates formed by any of the "juxtaposing" mechanisms is brought about chiefly by organic and inorganic colloids. Baver (1956), amongst others, has stated that stable aggregation cannot take place in sands and silts in the absence of colloids. Three major groups of stabilizing agents are generally recognized: clay, sesquioxides of iron and aluminium, and humus, but there is no general agreement about their relative importance. Baver (1956), and Arca and Weed (1966) have shown the importance of clay, though the latter workers found that its effects were confined largely to micro-aggregates (those <0.5 mm.). Bennett 1926), Lutz (1934, 1936), and Arca and Weed (1966) all found that iron oxide was an important stabilizing agent, but Deshpande *et al.* (1964) found that the stability of macro-aggregates (2-3 mm.) was not dependant on the presence of iron oxide, and suggested that aluminium oxide is more important. Numerous workers have demonstrated the importance of humus as an aggregate stabilizer; Robinson and Page (1951), in particular, interpreted its importance as a water-proofing seal reducing swelling in clay-cemented aggregates. A number of workers, including Swaby (1949) and Harris *et al.* (1964) have described the aggregate-stabilizing effect of soil microflora and microfauna in addition to the more widely recognized agents. While there is no general agreement on the relative importance of different stabilizing agents, it is certain that there is considerable variation between soils, and aggregates may be stabilized by any one or more of the agents.

In order to assess the relative importance of different stabilizing agents in the sample soils, correlation coefficients were calculated between clay content, humus content, and aggregate stability as indexed by the percentage-weight of water-stable aggregates >3 mm. When all samples are considered the correlation levels are approximately the same (Table 2), indicating comparable importance as stabilizing agents, but when samples are split into sub-groups, the complementary importance of the two agents appears clearly. Where the correlation of aggregate stability with clay content is high, that with humus content tends to be low, and *vice versa.* When the clay content is relatively high, as in group 5, variations in aggregation appear to be controlled by humus content, but where humus content is high, as in group 2, clay content become diagnostic.

Although correlations between clay content, humus content and aggregate stability are generally significantly high, in no case do they, or the regressions

Table 2. Correlation between clay and organic matter contents, and aggregate stability for different sample sub-groups.

Sample Sub-group	Aggregate stability: Organic matter. *r*	Aggregate stability: Clay content. *r*	Clay %	Organic Matter %
1. All soils	.52	.56	20.05	2.60
2. Grassland Soils	.32	.51	23.82	2.92
3. Woodland soils	.63	.56	13.18	1.96
4. "Gritstone" soils	.49	.53	15.09	1.94
5. "Shale" soils	.62	.47	30.06	2.43
6. "Limestone" soils	.30	.41	23.23	4.27
7. Brown earths	.60	.69	19.50	2.37
8. Podzolic soils	.54	.40	16.97	2.25

(Fig. 6), indicate direct relationships. This is partially a reflection of the importance of other stabilizing agents in some soils. No facilities were available to measure sesquioxide content, but correlation of field observation with laboratory results indicates that they are of importance only in the illuvial horizons of highly-leached soils, and in the basaltic soil. It is frequently assumed implicitly that "juxtaposing" mechanisms are virtually ubiquitous, and therefore that aggregation variations, are a result of variations in the abundance of stabilizing agents. While this may sometimes be the case, the indirect relationships between stabilizing agents and aggregate stability observed in the sample soils are certainly partially due to variations in "juxtaposing" mechanisms. Particularly important are variations in the extrinsic factor of vegetation, which exerts a direct juxtaposing force through root pressure, and also acts indirectly as a stabilizing agent, by influencing humus content.

The dominant pedogenic factors controlling aggregation are parent material and vegetation, through their control over clay and humus contents, but climate and time as reflected by degree of leaching and maturity are important in influencing distribution of clay and humus within any soil. The data shown in Table 1 suggest that the woodland-grassland subdivision of samples is the most significant. This is supported by the aggregate size-distribution patterns (Figs. 1-4). Grassland soils all show the characteristics of stable well-aggregated soils, and very little structural deterioration with depth below the surface, while woodland soils show generally low concentration of aggregates in the >3 mm. category, and very marked structural deterioration with depth. Sample numbers did not permit a very subtle vegetation classification, and the significance of the classification is probably reduced as a result. No distinction was made between managed grasslands and rough grazing in classifying grassland soils. The former is dominated by *Festuca ovina* with rooting patterns very different from *Nardus stricta*, which dominates the rough grazing. Likewise no distinction could be made between soils of calcareous and siliceous woodlands (Moss, 1913), or between natural woodland and forestry plantation soils. Nevertheless the diagnostic importance of vegetation can be seen clearly in aggregate size-distribution patterns (Figs. 1-4). Surface horizons of grassland soils over all parent materials show basically the same aggregation, while comparison of profiles 12 and 36 indicates that surface horizons of soils developed under *Calluna* heath also have similar aggregation patterns regardless of differences in parent materials.

The significance of the woodland-grassland division and the generally lower stability of woodland soil aggregates is due chiefly to differences in rooting and in the mechanism of addition of humus to the soil. The large, sparse, woody roots of woodland soils have little binding effect on aggregates, and decay very slowly adding humus only to very restricted areas within the soil. The rooting of grassland soils, on the other hand, consists of a dense mesh of fine rootlets and root hairs, which help to bind aggregates, and decay rapidly providing abundant humus for aggregate stabilization, intimately intermixed within the mineral soil. In grassland soils the chief addition of humus is through root decay, whereas in woodland soils it is through leaf-fall. This leads to segregation of humus into surface horizons in woodland soils, and corresponding rapid deterioration of structural condition with depth.

Although vegetation type is the primary factor governing distribution of humus beneath the surface, and its incorporation into the mineral soil, the action of soil fauna is also important. This action, in particular that of earthworms, is minimal in highly-leached soils with pH values below 5, again tending to produce segregation of humus in surface horizons. In the Peak District woodland persists chiefly on higher ground where soils are acid, so that a combination of factors reduce deep penetration of humus.

While the stability of aggregates in surface soils and the decline of stability with depth is chiefly a function of humus content, aggregate stability in lower horizons is governed largely by clay content. Where this is high the structural decline with depth is not marked, and in some soils an increase in stable aggregation is seen, despite decline in humus content (Fig. 3). Clay percentage in these soils is a function primarily of parent material (Bryan, 1969b) rather than weathering; as shale and basaltic rocks outcrop only over very restricted areas, clay-rich soils

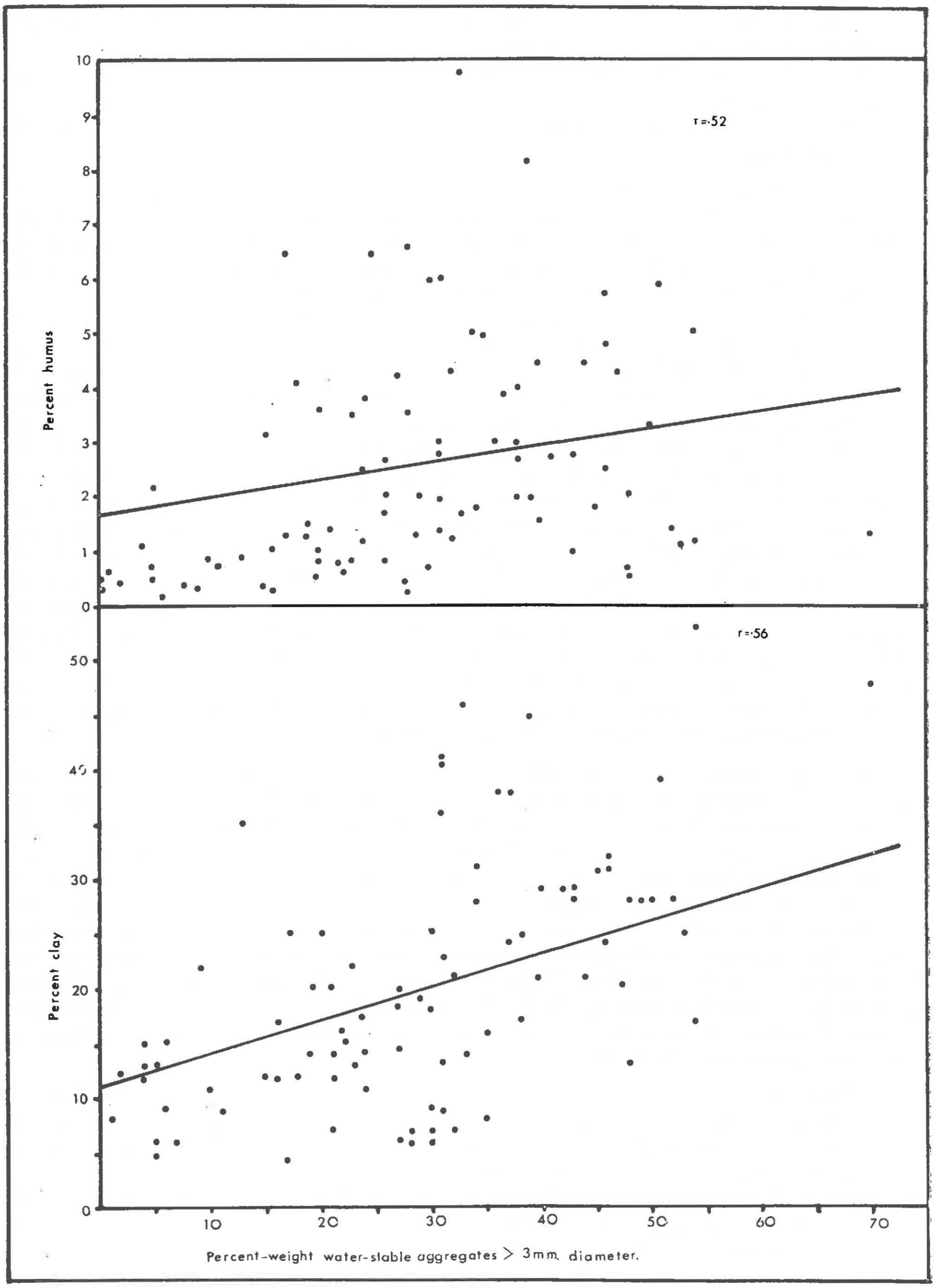


Figure 6. Regressions of clay and humus contents on aggregate stability.

are only of local significance. Clay contents of "limestone" and "gritstone" soils are both low, although that of the "limestone" soils is appreciably higher.

Relationship of aggregation characteristics to soil maturity

The existence of a relationship between aggregation characteristics and maturity has already been indicated in Table 1. The greater stability of the aggregates in brown earths compared with those of podzolic soils cannot be explained in terms of relative contents of clay or humus (Table 2) or entirely by vegetation contrasts. The classification of soils into brown earths and podzolic soils is a very generalized edition of a much more detailed classification of Peak District soils into climosequences (Bryan, 1967a). It is not certain whether these climosequences are also sequences of maturity, or whether they represent a hierarchy of mature soils. In either case, they certainly represent a sequence of increasing soil development, and their geomorphological significance is therefore the same as though they constituted maturity sequences.

The chief difficulty encountered in attempting to assess the relationship between soil maturity and aggregation is the isolation of an objective criterion of maturity. Probably the most widely accepted criterion is slope angle, maturity being held to increase as slope angle decreases. While this is undoubtedly true in some cases (Furley, 1968), it cannot be applied everywhere. It has been suggested (Bryan, 1967b) that the shape of slope and juxtaposition of slope facets are more important than slope angle in their effect on moisture balance in the soil. So a five degree slope facet may be the site of a very mature soil, or one in which development has been halted by excess moisture. In his discussion of the *Aufbereitung* concept Beckett (1968) limits the relationship between soil maturity and slope angle to the erosional zone. Furley (1968) further considered that within the erosional zone the sampling area must be one of uniform pedogenic environment. Within such an area he demonstrated a definite relationship between slope angle and soil parameters associated with maturity.

In view of the limitations suggested by Beckett (1968) and Furley (1968), and the pedogenic complexity of the Peak District, slope angle is not a reliable index of maturity for this study. Other criteria, such as pH value, must be eliminated for the same reasons. In an attempt to arrive at a criterion of maturity which is objective and which encompasses most parameters involved in soil maturity, the sample soils were grouped into six maturity classes by degree of development (Fig. 7). Even this classification does involve some subjective assumptions, such as the equation between sols bruns acides and brown calcareous soils. In Fig. 7 each sample has been classified and plotted against aggregate stability. Despite difficulties in assessing the extremes, due to low sample numbers, there appears to be a clear decrease in aggregate stability with increasing maturity, in the B horizons. The trend is not quite so clear amongst the A horizons; there is an apparent increase in stability between classes 1 and 3, and then a decrease. This increase is only apparent, however, for most of the low maturity soils are calcareous, which, as described above, have high aggregate stability, though many of the aggregates are below 3 mm. diameter. Use of a smaller mesh sieve would have produced a rather different picture.

Beckett (1968) has suggested a number of factors which could produce an increase in detachability with increasing maturity. These include intrinsic factors which affect aggregate stability, and extrinsic factors which affect soil disturbance. Amongst the extrinsic factors, increased incidence of windblow damage to trees, and increased runoff and erosion, both as a result of decreased permeability of sub-surface soils, are regarded as particularly important. Windblow damage is certainly most frequent in soil with impermeable sub-surface horizons, where rooting is restricted, but the pattern of increasing disturbance hazard indicated by Beckett is oversimplified. While windblow is high over mature soils, it is also frequently high in immature soils where bed-rock is close to the surface. The pattern would then show maxima at either end of the maturity sequence. Beckett's suggestion of increased incidence of runoff and erosion in more mature soils is supported by the results of laboratory testing on small runoff plots under simulated rainfall (Bryan, 1969a).

Beckett (1968) attributes the increase in windblow, and in the incidence of runoff and erosion, to decrease in sub-surface permeability as result of clay enrichment. Where such enrichment occurs it will certainly reduce permeability,

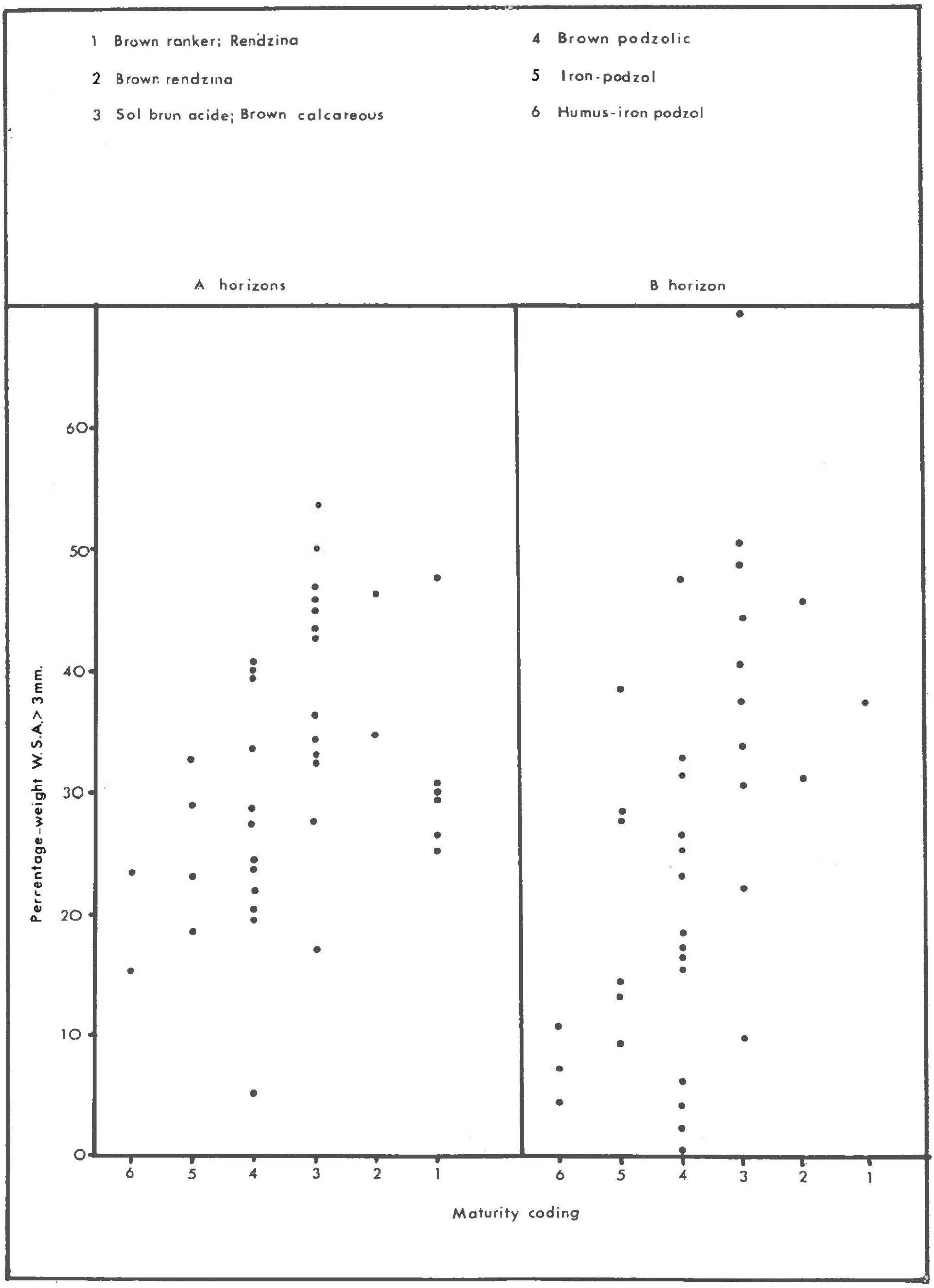


Figure 7. Relationship between aggregate stability and soil maturity.

and in accordance with the regression in Fig. 6, it should also increase aggregate stability. Although removal of clay from the surface soil certainly reduces aggregate stability there, it is doubtful if clay enrichment promotes much increase in aggregate stability in lower horizons. This is probably because clay deposition is in the form of clay skins and bridges around the aggregates, which increases the cohesion between the aggregates, but not within any given aggregate.

Although redistribution of clay with increasing maturity may explain changes in detachability in some soils, it certainly cannot explain the results obtained in this study. No convincing example of clay enrichment was seen, probably as a result of the prevailing coarse textures. Even if clay enrichment does not increase aggregate stability in the sub-surface soil, it certainly could not produce the decrease in aggregate stability observed (Fig. 7). The chief cause of the overall decrease in aggregate stability observed appears to be increasing leaching. As soils mature, base impoverishment becomes more complete, increasing acidity, and decreasing the earthworm population. As the earthworms decrease, the incorporation of humus within the mineral soil also decreases, leading to a decline in aggregate stability. While this sequence accounts for decline in aggregate stability with increase in maturity, it also explains the low aggregate stability of a brown ranker developed over gritstone (profile 27, Fig. 2).

PENCK'S *AUFBEREITUNG* CONCEPT

Although Beckett (1968) provides a considerable body of evidence to support part of Penck's concept, he rejects its application to concave slopes, and therefore the basis of Penck's ideas on slope evolution. This rejection is based in part on the distinction between soil detachability and soil transportability. In practice the distinction between these parameters is very nebulous. As Beckett has pointed out, detachability depends to a large extent on aggregate stability, while transportability depends on particle size and shape. Particle size and shape are, however, determined primarily by the resistance of aggregates to dispersion, and so transportability is governed by the same property as detachability. This does not nullify Beckett's argument, for transportability is also a function of the transporting capacity of runoff. As runoff passes on to the reduced gradient of the concave slope, its transporting capacity will be reduced, and material removed from the upper part of the slope will be deposited. This material is not immediately detachable or transportable, but after further development as part of the soil on the concave slope, and further *Aufbereitung*, it will become transportable, even by low velocity flow. This sequence of events demands, as Beckett correctly states, that detachment of material be episodic. Detachment by surface wash and splash is most frequently episodic, particularly on vegetated slopes, and in areas such as the Peak District where precipitation of sufficient intensity to produce runoff is comparatively rare (Bryan, 1969a).

Beckett suggests that Penck's concept must require that runoff be unsaturated for significant removal to occur on the concave slope. This is not necessarily the case, as the likelihood of runoff generation on the concave slope will increase with decreasing soil agregate stability. As Duley (1939), amongst others, has shown, low stability of aggregates in the surface soil will tend to promote surface sealing, thereby increasing runoff. Therefore, although the velocity of runoff on the concave slope will be reduced, consequent reduction in the transporting capactiy may be counteracted by increased volume of runoff.

The discussion above would suggest that the *Aufbereitung* concept can be applied to the concave slope, particularly as Penck's ideas on slope evolution would require most rapid removal from the steepest segments of the concave slope. On the other hand, Penck's concept assumes that the most mature soils are on the concave slope, presumably in areas of narrow interfluve ridges. In this study the most mature soils were developed above the convex slope, on the steepest section of the broad, almost flat interfluves. So, in the study area, strict application of the *Aufbereitung* concept would suggest that crest-lowering is more important than parallel retreat. This does not invalidate the concept when applied to areas of narrow interfluve ridges.

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