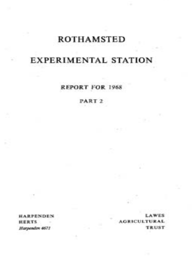
Rothamsted Experimental Station Report for 1968 - Part 2



ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1968

PART 2

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Full Table of Content

5. The Soils of Broadbalk. Morphology and Classification of Broadbalk Soils

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5. THE SOILS OF BROADBALK

Morphology and Classification of Broadbalk Soils

By B. W. Avery and P. Bullock

The Rothamsted soil was described by Lawes (1847) in his first paper to the Royal Agricultural Society as 'rather a heavy loam resting upon chalk, capable of producing good wheat when well manured; not sufficiently heavy for beans, but too heavy for good turnips or barley'. Reporting results of the first 20 years' work on Broadbalk, Lawes and Gilbert (1864) re-affirmed that the experiment was made 'upon what may be called fair average wheat land', and described the soil in more detail as 'a somewhat heavy loam, with a subsoil of raw yellowish red clay, but resting in turn upon chalk, which provides good natural drainage'.

Geology

In geological surveys of the Rothamsted estate, Woodward (1904) and Dines (1931) equated Lawes and Gilbert's 'raw yellowish red clay' with Clay-with-flints as delimited by the Geological Survey, and drew attention to the heterogeneous nature and irregular thickness of the deposit. Whitaker (1889) regarded Clay-with-flints as an essentially residual accumulation resulting from slow solution of chalk (Upper Chalk), with nodules and layers of flint. It now seems that subsurface solution *in situ*, accompanied by illuvial concentration of fine clay derived from materials above, has given rise only to a lithologically distinctive and widespread, but usually thin, accumulation resting directly on the irregular chalk surface (Loveday, 1962; Hodgson *et al.*, 1967). The thicker 'plateau drift' shown as Clay-with-flints on geological maps evidently comprises more or less weathered remains of water-laid sediments (chiefly Eocene clays and sands) overlying the Chalk, incompletely mixed with variable amounts of chalk residue (chiefly flint). Most British geologists have concluded that the materials were re-arranged under periglacial or glacial conditions during one or more of the earlier Pleistocene glaciations.

In and around Broadbalk, the Clay-with-flints contains irregularly distributed angular and subangular flints, and a few rounded flint pebbles. Dines (1931) considered that unabraded angular flints came direct from the Upper Chalk, subangular and generally iron-stained flints from old gravels once resting on the Chalk, and black flint pebbles from the Reading Beds or other lower Tertiary deposits. Occasional fragments of ferruginous sandstone unearthed in West Barnfield yielded fossils which led Dines and Chatwin (1930) to conclude that it was of Red Crag (lower Pleistocene) age. The matrix of the drift is generally a yellowish red, more or less mottled clay, but locally contains much sand, either in sharply defined

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pockets or modifying the clay. In Broadbalk, chalk is everywhere more than 5 ft down and may be more than 20 ft in 'swallow holes' or 'pipes' in the chalk surface.

General physical characteristics

Texture. Over most of the field, loamy and flinty soil overlies the brightly coloured Clay-with-flints at ess than 24 in. depth, and in places the clay has been brought to the surface by the plough. Hall (1917) quoted early mechanical analyses showing that the topsoil 'contains little coarse sand or grit, but a considerable amount of fine sand and silt, and a large body of clay. In consequence the soil has to be worked with care, becoming very sticky and drying to impracticable clods if moved when wet. It "runs together" if heavy rain falls after a tilth has been established, and then dries with a hard unkindly surface, these difficulties being much exaggerated on the plots which have been farmed for a long time without any supply of organic manures.'

The topsoil texture has been loosely described as 'clay loam' or even as 'clay', but particle-size analyses show that it is predominantly silt loam as defined in the United States Department of Agriculture classification (Soil Survey Staff, 1951), with some 19–27% clay and more than 50% silt (2–50 μ) in the mineral fraction <2 mm. Finer textured, chiefly silty clay loam, topsoil occurs locally where subsoil clay has been brought to the surface. The 'heavier' patches are clearly seen on a map of isodynes (lines of equal soil resistance measured by drawbar pull) constructed by Haines and Keen (1925) from dynamometer readings (Fig. 5·1). The heaviest includes plots 16–19 of section I: others, less pronounced, are centred in plot 6 of section I and plot 14 of section IV. Haines and Keen correlated clay content and drawbar pull, and concluded that major variations reflected natural heterogeneity rather than cultural effects, except for the small value throughout plot 2 (farmyard manure). However, the last could be partly natural, as field assessments indicate that the topsoil on this side of the field has a relatively low clay content throughout.

With so much silt (2–50 μ), the topsoil has a greater available-water capacity (Salter *et al.*, 1966; Peterson *et al.*, 1968) than more sandy soil of similar clay content, and also than the clayey subsoil. Hence, the capacity of the profile as a whole to retain available water varies with the thickness of the superficial silty layer. Salter and Williams (1969) gave the following values for Broadbalk soils with and without farmyard manure (FYM) for two depths.

	Available-water capacity (in inches)	
Treatment	*0–6 in. depth*	*0–12 in. depth*
Without FYM	0·82	1·92
With FYM	1·07	2·30

Stoniness and bulk density. Hall (1917) also quoted average weights/acre of 'fine dry soil' (passing a $\frac{1}{4}$-in. sieve) and stones for successive layers 9 in. thick in each of the chief experimental fields. According to Lawes and Gilbert (1882), these values were derived from weights of oven-dry fine earth and stones in samples of known volume. The results, used chiefly to re-

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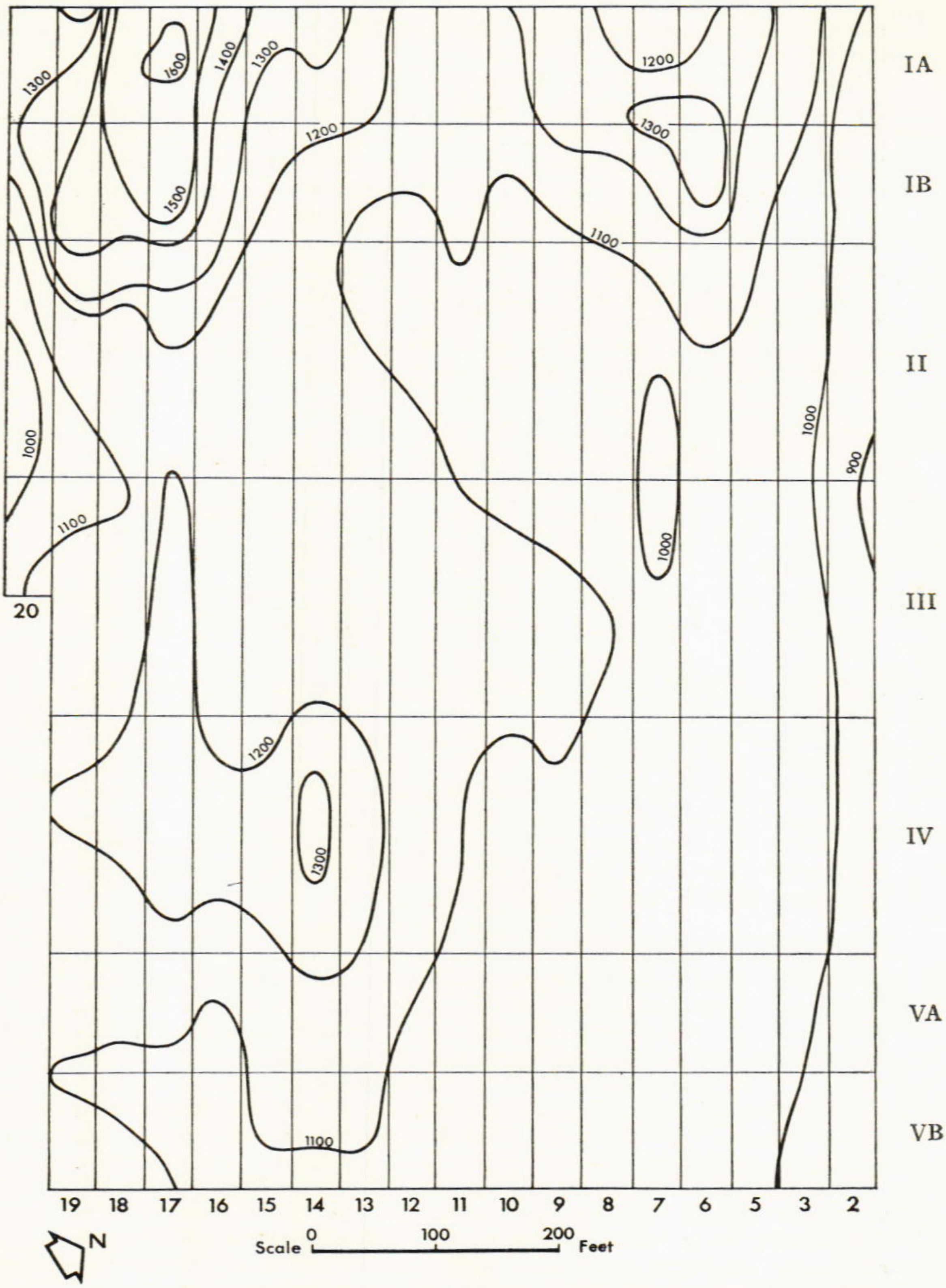

FIG. 5·1. Isodynes (drawbar pull in lb) in Broadbalk, after Haines & Keen (1925).

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calculate N determinations on a weight/acre basis, varied significantly in different years.

The mean values of stone content by volume and bulk density in Table 5·1 were calculated from the original data of the 1881 sampling (see Johnston, p. 93), when a box 6 in. × 6 in. × 9 in. deep was used, assuming that the mean specific gravity of flint is 2·60. The average stone content decreases significantly at successive depths from 10·5% in the upper 9 in. to less than half this value at 18–27 in., whereas the range of variation increases. However, because of the small size of the sampling box in relation to the average size of the flints, which usually increases with depth, the value for the lowest layer in particular is probably underestimated. The bulk density values decrease slightly with depth when stones are included: corresponding values for weight of dry soil per unit volume (excluding stones) are 1·39, 1·42 and 1·41 g/cc respectively.

TABLE 5·1

Mean stone content and bulk density (including stones) in successive layers of Broadbalk soil

	% stones > ½ in. by volume		Bulk density (g/cc)	
Sample depth	Mean of 20 plots	Coefficient of variation	Mean of 20 plots	Coefficient of variation
0–9 in.	10·49 ± 0·29	12·2%	1·514 ± 0·012	3·6%
9–18 in.	6·55 ± 0·54	37·1%	1·498 ± 0·012	3·5%
18–27 in.	3·88 ± 0·69	79·6%	1·451 ± 0·011	3·2%

Drainage is impeded to some extent by the slowly permeable, clayey subsoil, but systematic observations confirm morphological evidence (see below) that the soil is mainly moderately well drained (Hodgson, 1967 p. 44), implying that the rooting zone to a depth of 20 in. is seldom saturated with water for as long as a month at a time. However, after heavy rain, water lies on the low ground in the headland south-west of section V, and the topsoil is waterlogged for longer periods in places in section I, as shown by temporary gleying (Siuta, 1967) associated with undecayed stubble at the base of the ploughed layer.

Soil structure. Although the topsoil structure is somewhat unstable to water, there is no evidence that structural deterioration under continuous arable cultivation has influenced crop yields significantly (Boyd *et al.*, 1962). Using simple laboratory tests, Williams and Cooke (1961) confirmed Hall's observation that aggregates of Rothamsted topsoil slake in water, and the slaked soil had a small permeability, but similarly treated loamy sands and sandy loams slaked more severely and were less porous. Measurements of pore-size distribution showed that root growth was unlikely to be checked in the more clayey soil, but might be in sandy soils.

The Broadbalk soil evidently contains enough clay for frost and seasonal wetting and drying to promote aggregation and porosity, which are further favoured by the presence of added chalk. The relatively good drainage encourages deep rooting, so promoting intensive and persistent fissuring in the finer-textured subsoil.

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BROADBALK SOILS: MORPHOLOGY AND CLASSIFICATION

Profile characteristics

The Rothamsted soils were first studied and mapped on a profile basis by Lee (*Rothamsted Report for 1931*, p. 40). During the last 20 years, profiles of soils formed in Clay-with-flints and associated deposits have been studied and classified by the Soil Survey of England and Wales (Avery, 1964; Hodgson, 1967). Several soil series have been distinguished, and soil maps of the Rothamsted estate have been published in the Station Guide. Gerasimov & Chichagova (1960) published a paper giving morphological and chemical characteristics of profiles in Highfield and Broadbalk, following a visit by Gerasimov in 1958, but Rodé (1960) subsequently questioned their conclusions about the origin and development of the Broadbalk soil.

Avery (1964) noted that characteristic features of semi-natural forested soils on the Chilterns had been extensively modified by long continued cultivation and ameliorative measures, accompanied on sloping ground by some erosion. An estate map of 1623 shows that Broadbalk, then known as Lower Sheepcote Field, had been farmed as an enclosed field for at least two centuries before Lawes began his experiments, and it was probably cultivated much earlier. In addition to the effects of tillage and manuring, the original profile has been disrupted in places by extracting chalk, and also by tile drainage (see Johnston and Garner, p. 22). The field has a maximum slope of about 2° in parts of sections IV and V, and slight erosion has evidently occurred.

The average depth of ploughing is now 8–9 in.: on plots 2A and 2B that have had farmyard manure annually, the ploughed layer is dark greyish brown when moist (rubbed colour approximating 10YR 4/2 in the Munsell notation), whereas on other plots it has an appreciably brighter colour (10 YR 4/3), reflecting the generally small organic-matter content.

The practice of sinking pits to dig chalk and spreading it on the surface was well established by the 18th century (Young, 1813; Russell, 1916), and large amounts were applied to arable land on the originally acid soil of the Chiltern plateau. The sites of the 'bell-pits' from which chalk was extracted are perceptible today as shallow depressions or 'dells'. The first analyses of the Broadbalk topsoil show up to 5% calcium carbonate, but there is no record of when the chalking was done. Eight dells are shown on the drainage plan of 1851 but it is not known whether all the chalk used on Broadbalk was from these dells. Figure 5·2 shows their sites.

Profile variants. In a detailed soil survey, four profile variants were distinguished by thickness, texture and colour of sub-surface horizons (Fig. 5·2). Their distribution was mapped by traversing each section and subsection (as sub-divided in 1968), and augering in pathways between plots to avoid previously disturbed ground. One hundred and ninety borings were made, and the delineated boundaries enclose areas within which more than 85% of the observations conform to the variant indicated in the map legend.

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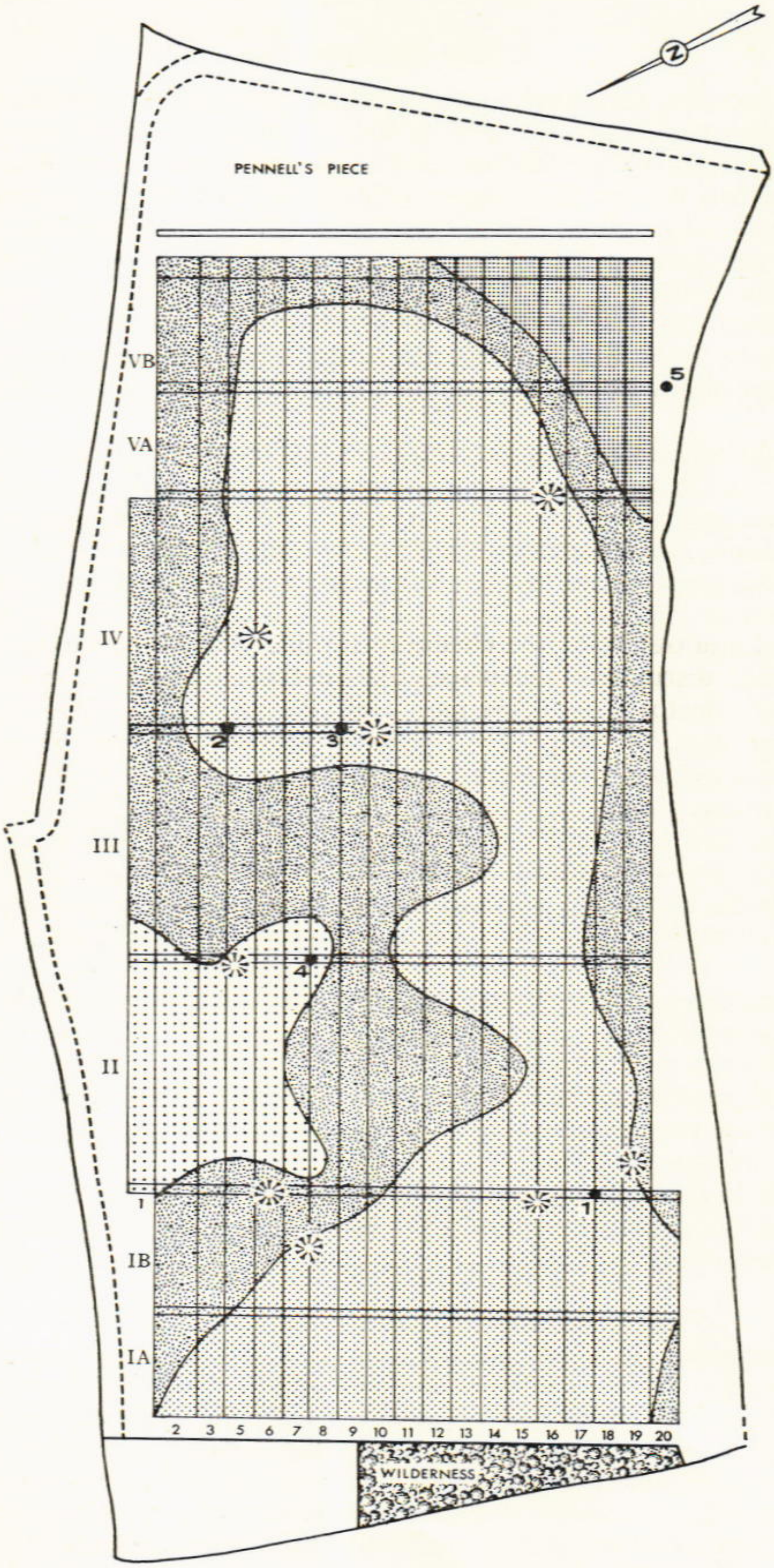

FIG. 5·2. Soil Profile Variants in Broadbalk. (See key opposite).

Variants A and B, together occupying some 90% of the field, are soils of the *Batcombe* series (Avery, 1964), which occur widely on the Chiltern plateau and similar terrain south of the Thames. The soil has greyish brown to brown, loamy and flinty upper horizons, passing more or less abruptly into yellowish red or strong brown clay at less than 24 in. depth. In variant B, which is more extensive generally, the topsoil is a silt loam, over a brown sub-surface horizon of similar or rather finer texture; in variant A, chiefly confined to cultivated land, the clay is just beneath the ploughed layer, and the topsoil can have a silty clay loam or clay loam texture. The clayey B horizon, with a more or less well defined blocky structure, is characteristically mottled and streaked with red, brown and greyish colours, and a network of fissures with grey faces extends deeper, facilitating slow seepage into the underlying chalk.

Morphological, granulometric and mineralogical studies of *Batcombe* profiles in Buckinghamshire and Oxfordshire by Loveday (1958) and Avery *et al.* (1959) showed that the characteristic textural change with depth is due partly to the general occurrence of a distinct silty superficial deposit overlying and intermixed with the Clay-with-flints, and partly to downward movement of clay-size particles (*lessivage*) within the composite parent material. The soil was thus classified as a *sol lessivé* (brown earth with textural B horizon) with gleying. The Clay-with-flints subsoil itself is thought to comprise disturbed or partially truncated remains of deeply weathered profiles originating in interglacial or Tertiary periods of warmer climate. In this respect, as in morphology, the soil resembles 'red-yellow podzolic soils' in similar materials in eastern United States.

Variant C is a phase of the *Hook* series (Hodgson, 1967), with brown friable silt loam passing into a firmer, mottled, silty clay loam subsoil, over Clay-with-flints at depths exceeding 24 in. The silty layer usually has few stones below the topsoil, and is thought to be weathered loess or 'brick-earth' comparatively unaffected by admixture with the material below. This variant occurs on the Chiltern plateau in small areas surrounded by

Profile Variant	*Definitive sub-surface characters.*
A	**Yellow-red clay, locally sandy, at less than 12 in. depth.**
B	**Brown, silty; over yellow-red clay, locally sandy, at 12–24 in. depth.**
C	**Brown, silty, with few flints, to more than 24 in. depth.**
D	**Brown, silty and flinty, to more than 24 in. depth or over silty layer with few flints.**
	Dells, from map of 1851.
•5	**Profiles described and sampled.**

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Batcombe soil, often in shallow depressions. On Broadbalk it covers rather less than an acre in plots 1–8 of section II, and has also been identified in isolated borings elsewhere.

Variant D occurs in a shallow dry valley which crosses the south-eastern corner and heads in the adjoining Pastures field. It has a sub-surface horizon of brown flinty silt loam, which locally becomes gravelly at the base, and rests either on a mottled silty layer with few stones, or on Clay-with-flints at depths greater than 24 in. The morphology and geomorphic position suggest that the upper layer is colluvium, moved downslope in late-glacial times or since the land was first cultivated. It resembles the *Nettleden* series defined by Avery (1964), except that lower horizons are gleyed.

Morphology of representative profiles

Undisturbed 6 in. cores were extracted by a Proline soil corer for detailed description and sampling. Profiles were described using the terminology for soil colour, texture, structure and consistence defined in the U.S.D.A. Soil Survey Manual (Soil Survey Staff, 1951). Thin sections of selected horizons were prepared after impregnation with Autoplax 110 resin, and described using Brewer's (1964) terminology. Soil samples (<2 mm) from each horizon were used for particle-size and chemical analyses (Table 5·2), and for mineralogical studies.

Descriptions of five profiles are given below, and Fig 5·2 shows their location. The first two conform to variant A; the third to variant B, and the fourth and fifth to variants C and D respectively. Conclusions about the origin and development of the profiles, from the morphological, granulometric and mineralogical studies, are summarised by Catt (p. 89).

The horizon designations accord with the scheme used by the Soil Survey of England and Wales (Hodgson, 1967, p. 39), and are based on macro-morphological, micro-morphological and particle-size data. The following suffixes are used: t denotes a B horizon with evidence of significant illuvial enrichment in clay-size particles (argillic horizon); g (gleyed) is applied to horizons with common or many, distinct or prominent, greyish and ochreous mottles attributable to reduction and segregation of iron as a result of intermittent saturation with water: where mottling is weaker, the symbol (g) is used. Ap represents a ploughed surface horizon, and Eb a brownish sub-surface horizon from which clay-size material has evidently been removed. The location of thin-section samples is noted in the descriptions.

Profile 1 (***variant A***)***:*** between sections I and II, and plots 17 and 18.

Ap	0–8 in.	Dark brown (10 YR 4/3–4/2) flinty clay loam to silty clay loam; friable to firm when moist, hard when dry and plastic when wet; irregular clods with weak fine and medium blocky structure; slightly calcareous (added chalk); few fine ferrimanganiferous nodules; few roots; sharp boundary.

https://doi.org/10.23637/ERADOC-1-2

II B1t(g)	8–20 in.	Yellowish red (5 YR 5/6–5/8) to strong brown (7·5 YR 5/6) flinty clay with common, fine to medium, red (2·5 YR 4/6) mottles and few, fine, brown (7·5 YR 5/4) to pale brown (10 YR 5/3) mottles, chiefly in the lower part; smooth brown (7·5 YR 5/4) faces enclosing stones; very firm when moist, very hard when dry and very plastic when wet; ill defined (in core) coarse blocky structure; occasional channels partly filled with dark topsoil material; few diffuse ferrimanganiferous concentrations; roots rare; merging boundary.
II B2t(g)	20–37 in.	Similar, yellowish red, strong brown and red, faintly mottled clay with fewer flints; common mottles and sub-vertical streaks of brown (7·5 YR & 10 YR 5/4–5/3) and (locally) light brownish grey (10 YR 6/2); very plastic when worked in the wet condition, but crumbles readily before moulding when partly dried; greyish inclusions are relatively plastic and apparently more clayey than the matrix; roots rare.

Profile 2 (***variant A***)***:*** between sections III and IV, and plots 3 and 5.

Ap	0–8 in.	Dark brown (10 YR 4/3) flinty silt loam; friable when moist, hard when dry and slightly plastic when wet; irregular clods with weak, fine and medium, sub-angular blocky structure; slightly calcareous (added chalk); few roots; sharp boundary.
II B1t(g)	8–20 in.	Yellowish red and strong brown (5 YR–7·5 YR, 5/6–5/8), slightly flinty clay with few to common, fine and medium, red (2·5 YR 4/6) mottles and common, faint, paler brown (7·5 YR 5/4) mottles and ped faces, becoming more evident with increasing depth; very firm when moist, very hard when dry, and very plastic when wet; moderate, medium to coarse blocky structure with smooth shiny ped faces, locally striated (slickensided); few channels partly filled with top-soil material and earth-worm casts; few fine ferri-manganiferous nodules; few roots; merging boundary. (Thin section at 15 in.)
II B2tg	20–38 in.	Yellowish red (5 YR 5/6–5/8) and strong brown (7·5 YR 5/6) flinty clay with few to common red mottles as above; common, brown to greyish brown (10 YR 5/3–6/2) mottles and few light grey (10 YR 6/1) mottles or streaks, occurring chiefly in association with cleavage planes or channels, and around stones; very firm when moist and very plastic when wet; ill defined (in core) coarse blocky structure with some smooth striated (slickensided) faces; soft diffuse ferrimanganiferous concentrations common in the lower part, few elsewhere; moisture glistening where stones are embedded; roots rare; merging boundary.

https://doi.org/10.23637/ERADOC-1-2

II Bt(g)/C	38–68 in.	Similar, strong brown to yellowish red clay containing scattered, little-broken nodular flints with thick white patina; red and brown mottles as above, becoming fewer; prominent grey coatings around stones and bordering occasional cleavage planes; very plastic when moulded in the wet condition, but crumbles before moulding when moist, especially where black manganiferous deposits are locally abundant; no roots. (Thin section at 54 in.)

Profile 3* (*variant B*)*: between sections III and IV, and plots 8 and 9.

Ap	0–7 in.	Dark greyish brown (10 YR 4/2·5) flinty silt loam; friable when moist, hard when dry and slightly plastic when wet; cloddy, with weak to moderate, fine and medium subangular blocky structure within clods; few fine ferrimanganiferous nodules; sharp boundary.
B1t	7–19 in.	Brown (7·5 YR 4/4), slightly flinty, silty clay loam with darker (7·5 YR 4/2) ped faces in the upper part and few faint paler brown mottles and ped faces in the lower part; friable to firm when moist, hard when dry and plastic when wet; moderate, medium to coarse blocky structure; few channels partly filled with dark topsoil material; few black manganiferous nodules throughout, and common diffuse ferrimanganiferous concentrations at 14–19 in.; few roots; narrow boundary. (Thin sections at 10 and 18 in.)
II B2t(g)	19–28 in.	Strong brown (7·5 YR 5/8) to reddish yellow clay with few small angular flints and flint pebbles; many medium and coarse red (2·5 YR 4/8) mottles and few, fine to medium, light grey (10 YR 7/1) mottles and streaks, becoming common in the lower part; ill-defined (in core) blocky structure; very firm when moist, very hard when dry and very plastic when wet; red material appears more friable and grey material more plastic; roots rare; merging boundary. (Thin sections at 21 and 27 in.)
II B3tg	28–40 in.	Strong brown to yellowish red (7·5 YR–5 YR 5/8) clay with appreciable fine sand and few small stones as above; common, fine to medium, red and light grey mottles, the grey colours occurring mainly around stones and as subvertical streaks associated with cleavage planes or old root channels; less plastic than above; ill-defined (in core) blocky structure; roots rare; merging boundary.
III Btg/C	40–60 in.	Yellowish red to strong brown (yellower with depth) clay loam with appreciable sand and rare small stones; few red mottles and common to few, light grey mottles and subvertical streaks; the red mottles becoming finer

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and fewer with increasing depth; firm to friable (when dug out); moderate medium platy structure; no roots. (Thin section at 51 in.)

Profile 4 (variant C): between sections II and III, and plots 7 and 8.

	Ap	0–9 in.	Dark greyish brown (10 YR 4/2–4/3) flinty silt loam; friable when moist, hard when dry and slightly plastic when wet; cloddy, with weak, fine to medium, subangular blocky structure within clods; few fine ferrimanganiferous nodules; rare added chalk fragments; roots rare; sharp boundary.
	Eb/Bt(g)	9–16 in.	Brown (9 YR 4/4) slightly flinty silt loam with darker ped coatings in the upper part and common, faint, fine, lighter brown (10 YR 5/3) and strong brown mottling in the lower part; friable when moist, hard when dry and slightly plastic when wet; weak fine subangular blocky structure; common channels containing darker topsoil material, partly as worm casts; few fine ferrimanganiferous nodules; roots rare; narrow boundary. (Thin section at 12 in.)
	B1t(g)	16–26 in.	Brown (7·5 YR 4/4–5/6) silty clay loam with few small stones; common to many, fine and medium, pale brown (10 YR 5/3–6/3) mottles, and few fine light brownish grey (10 YR 6/2) mottles and sub vertical streaks; ped faces mainly pale brown, with common visible clay skins (argillans); firm when moist, hard when dry and plastic and sticky when wet; moderate medium subangular blocky structure; common channels with dark granular infillings as above; few irregular diffuse ferrimanganiferous concentrations; roots rare; merging boundary. (Thin section at 22 in.)
	B2tg	26–37 in.	Pale brown (10 YR 5/3–6/3), strong brown (7·5 YR 5/6) and light brownish grey (10 YR 6/2), distinctly mottled silty clay loam to silty clay with few small stones; the greyish colours occurring chiefly as subvertical streaks; firm when moist, plastic and sticky when wet; ill-defined (in core) blocky structure; few channels as above; common ferrimanganiferous concentrations, locally weakly cemented; roots rare; narrow boundary. (Thin section at 30 in.)
II	B3tg	37–46 in.	Yellowish red (5 YR 5/8) and strong brown, very flinty, silty clay loam with common to many, fine and medium, pale brown to light grey (10 YR 6/1) mottles and faces where flints are embedded; common to abundant black manganiferous concentrations, locally weakly cemented; flints mainly small, angular and subangular; plastic when worked wet, firm to friable when moist; structure ill-defined (in core), partly fine blocky; no roots.

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***Profile 5* (*variant D*):** between sections VA and VB, in headland beside plot 19.

Ap	0–10 in.	Dark greyish brown (10 YR 4/2) flinty silt loam; friable when moist, hard when dry and slightly plastic when wet; weak fine subangular blocky structure; few fine ferrimanganiferous nodules; few roots; narrow boundary.
B1	10–16 in.	Brown (7·5 YR 4/4) flinty silt loam with some darker (10 YR 4/2) ped faces and few channels partly filled with dark granular soil; friable when moist, hard when dry and slightly plastic when wet; common fine ferrimanganiferous nodules; roots rare; merging boundary. (Thin section at 14 in.)
B2(g)	16–21 in.	Brown (7·5 YR 4/4–5/4), flinty to very flinty silt loam with common, fine, pale brown (7·5–10 YR 6/3) and reddish brown (5 YR 4/4) mottles; few partly filled channels; common black ferrimanganiferous nodules and diffuse concentrations; roots rare; narrow boundary.
II B′1g	21–28 in.	Brown (8 YR 5/4) silty clay loam with few small stones; common, fine, light brownish grey (10 YR 6/2) and strong brown (7·5 YR 5/6) mottles, and few fine light grey (10 YR 6–7/1) mottles; common black ferrimanganiferous concentrations; friable to firm when moist and slightly plastic when wet; weak medium blocky structure; no roots; merging boundary.
II B′2(t)g	28–36 in.	Strong brown (7·5 YR 5/6–5/8), brown and light brownish grey (10 YR 6/2), coarsely mottled silty clay loam with few stones as above, and common to abundant dark brown to black ferrimanganiferous concentrations, locally weakly cemented; greyish colours occurring partly as sub vertical streaks; plastic when wet and firm to friable when moist; ill-defined (in core) blocky structure; no roots. (Thin section at 34 in.)

Profiles 1 and 2. In profiles 1 and 2 conforming to the *Batcombe* series, the sharply defined Ap horizon rests directly on a finer textured Bt horizon, indicating that the sub-surface Eb horizon normally present in analogous uncultivated soils has either been incorporated in the ploughed layer or removed by slight erosion (Avery, 1964).

In each, the Bt horizon consists throughout of yellowish red clay with blocky structure and red, brown and greyish mottles. There is no distinct C horizon, the Bt horizon grading downwards into similar material intersected by widely spaced planar cleavages, often inclined at acute angles to the horizontal. The red mottles, which resemble those in corresponding horizons of many 'red-yellow podzolic soils' (Ultisols) in acidic materials, could conceivably have been inherited unchanged from Eocene (Reading Beds) clay. However, the general occurrence of similar morphological features in deeply weathered plateau deposits of diverse origin, suggests that they result from pedological re-organisation in a lengthy, late Tertiary

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(Broek & Waals, 1967) or early Pleistocene period. Colours of lower chroma, attributed to reduction, or reduction and local translocation of iron (Bloomfield, 1951; Blüme, 1968), are distinct below about 20 in. in profile 2, and occur chiefly on ped faces, around stones and bordering wavy or striated (slickensided) planes.

Thin sections at 15 and 54 in. in profile 2 show a sepic porphyroskelic fabric typical of *Braunlehm* and *Rotlehm* (Kubiena, 1953). Sand and silt grains are unevenly distributed in the dense plasma, most of which is moderately or strongly oriented, the remainder having a weak or flecked orientation. Thin argillans are associated with some voids, especially in the upper section, but nearly all the strongly oriented clay occurs as plasma separations, or as concentrations unassociated with existing voids. There are also discrete clay papules. This orientation pattern is probably due to pressures and tensions resulting from wetting and drying (Brewer, 1964, p. 339), as evidenced by the occurrence of slickensided planar voids in the lower horizon.The red mottles appear as diffuse irregular ferruginous concentrations, the centres of which are deep red and generally lack birefringence; in less dense parts, the iron-rich plasma is locally strongly oriented, and encloses skeletal grains, papules and zones of yellowish oriented clay. Channels and pores traversing reddened areas are lined with yellowish, strongly oriented clay, indicating that the red mottles are relict features. Dark brown, diffuse, ferrimanganiferous concentrations and discrete nodules are also common in both sections.

Profile 3. Red-mottled clay is encountered at 19 in. depth in profile 3, the upper part of the B horizon consisting of brown, relatively friable, silty clay loam with thick argillans on ped faces and only faint mottling. The clayey II B2t(g) horizon contains appreciable sand, and merges downwards into coarser textured, laminated material with few stones. Similar materials occur sporadically within or below Clay-with-flints at many places on the Chiltern plateau, and are possibly lacustrine deposits originally accumulated in 'swallow holes'.

Variations in the distribution of sand- and silt-size grains in thin sections from this profile confirm a definite lithological discontinuity at about 19 in. and another, less definite, at 40 in. The B1t horizon has a more porous (porphyroskelic) fabric than in profile 2 and most of the plasma is unoriented or weakly oriented. Strongly oriented clay occurs chiefly as prominent argillans on void walls, and as intra-ped concentrations. The II B2t horizon below has a denser porphyroskelic fabric resembling that in the sub-surface Clay-with-flint horizons of profile 2, except that concentrations of oriented clay are more clearly evident, those in the lower part being often bleached. Diffuse, irregular, ferruginous concentrations (red mottles) are most abundant in the upper part, constituting up to 80% of the fabric. The section in the lowermost, laminated horizon (III Btg/C) is more porous, with much less moderately to strongly oriented clay, chiefly as thick, partly bleached argillans lining channels or planes. The fabric is very heterogeneous, some parts having almost no plasma, and comprises depositional laminae, Red ferruginous concentrations are less common than in the horizon above, but irregular brown nodules are locally abundant.

https://doi.org/10.23637/ERADOC-1-2

Profile 4. In the *Hook* series profile, the horizons to a depth of 37 in. are in a silty superficial deposit, which overlies a very flinty layer; red-mottled Clay-with-flints occurs only below 46 in., the maximum depth penetrable by the corer. A brown friable sub-surface horizon passes at 16 in. into a firmer and finer textured Bt horizon, with strong brown and greyish mottling more pronounced with increasing depth. The thin section in the upper Eb/Bt(g) horizon shows a porous, predominantly asepic fabric with some prominent, moderately or strongly oriented argillans around pores, possibly formed by inwash of fine clay since the soil was cultivated. Sections in the Bt horizons below have much more strongly oriented clay, mainly in argillans, but most of the plasma remains unoriented or weakly oriented. All three horizons, especially the lowest, show evidence of segregation of iron and manganese, bleached patches occurring in association with nodular or diffuse concentrations, but red ferruginous segregations are notably absent.

Profile 5. Below an Ap horizon thicker than usual, the sub-surface horizons of profile 5 are of brown flinty silt loam, more flinty and distinctly mottled below 16 in., and changing sharply at 21 in. to a mottled silty layer with few stones, resembling the B horizons of profile 4. The morphology suggests that the horizons above 21 in. comprise a different and more recent deposit which has buried a truncated gleyed soil like the Park Gate series (Hodgson, 1967). The former horizons are therefore designated B rather than Eb. The thin section at 14 in. shows an intertextic fabric with a plasma of intimately mixed clay and organic matter, and little or no strongly oriented clay.

The silty horizons underneath are designated B′g, the addition of a prime accent indicating that they are interpreted as buried horizons. The thin section of the lowest horizon has much less strongly oriented clay than in the Bt horizons of profile 4, and few argillans. Most notable is an abundance of ferrimanganiferous concentrations, mainly diffuse and penetrating some 75–80% of the fabric. Segregation of iron and manganese in this profile has undoubtedly been influenced by intermittent saturation with laterally moving ground-water, which may also have affected the distribution of clay.

Analytical data on representative profiles

Particle-size distribution. Particle-size analyses were made on samples from each horizon of the profiles described. The samples were pre-treated with H_2O_2, washed with ethanol and oven-dried, weighed, and dispersed by shaking overnight with sodium hexametaphosphate. Fractions $<2\ \mu$ and 2–20 μ were determined by pipette sampling; and 50–100 μ, 100–200 μ and 200–2000μ fractions by sieving, using B.S. 300, 150 and 72 sieves respectively; and the 20–50 μ fraction by difference (Table 5·2).

Except in profile 1, in the heaviest part of the field, the Ap horizons are silt loams, with between 19 and 25% clay. The Bt horizons have at least a third more clay, and in profiles 1 and 2 the clay content rises sharply at the base of the Ap horizon to more than 50% in the Clay-with-flint B1

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TABLE 5·2

Particle-size and chemical data on representative profiles

Profile No.	Horizon	Depth (in.)	Particle-size distribution (% in oven-dry peroxidised soil) 200μ–2 mm	100–200μ	50–100 μ	20–50 μ	2–20 μ	<2μ	Organic carbon %	$CaCO_3$ %	Free Fe_2O_3 %	Exch. H^+ m.e. %	C.E.C. m.e. %	Base saturation %	pH H_2O	pH 0·01M–$CaCl_2$
1	Ap	0–8	6·4	13·7		26·8	24·6	28·4	1·0	1·3	n.d.	n.d.	n.d.	n.d.	8·1	7·4
	IIB1t(g)	8–20	2·3	6·2		18·5	18·0	55·0	0·5	—	n.d.	n.d.	n.d.	n.d.	7·8	7·2
	IIB2t(g)	20–37	2·1	8·5		15·2	15·5	58·8	0·3	—	n.d.	n.d.	n.d.	n.d.	7·6	7·0
2	Ap	0–8	6·0	4·8		38·9	26·6	23·6	n.d.	1·5	2·6	n.d.	15·8	n.d.	8·1	7·6
	IIB1t(g)	8–20	2·0	2·7		22·7	15·9	56·8	n.d.	Tr.	5·2	0·9	31·5	97	7·8	7·2
	IIB2tg	20–38	1·8	9·5		7·9	10·3	70·6	n.d.	—	6·5	n.d.	n.d.	n.d.	7·5	7·0
	IIBt(g)/C	38–68	4·3	7·1		9·6	9·3	69·7	n.d.	—	5·6	1·4	34·1	96	7·4	6·8
3	Ap	0–7	5·7	9·5	4·9	31·0	24·3	24·7	0·9	0·3	3·2	0·6	16·0	96	7·9	7·3
	B1t	7–19	2·2	7·5	3·4	26·1	24·0	36·8	0·5	—	4·1	1·4	20·9	93	7·6	7·0
	IIB2t(g)	19–28	2·5	22·0	8·4	8·5	8·7	49·8	0·3	—	4·4	0·8	23·9	97	7·6	7·0
	IIB3tg	28–40	5·2	16·2	8·6	18·6	8·4	43·0	n.d.	—	4·4	n.d.	n.d.	n.d.	7·6	7·0
	IIIBtg/C	40–60	8·9	15·2	9·4	20·3	11·7	34·5	n.d.	—	4·0	1·2	14·7	92	7·5	6·9
4	Ap	0–9	5·4	8·8	4·4	34·5	28·0	18·9	0·6	0·3	2·2	n.d.	15·0	n.d.	8·1	7·6
	Eb/Bt(g)	9–16	3·5	4·2	3·6	32·3	31·9	24·5	0·5	0·2	2·9	0·7	15·7	96	8·0	7·5
	B1t(g)	16–26	0·7	1·1	1·7	26·6	31·2	38·8	0·4	Tr.	2·9	0·7	23·2	97	7·9	7·3
	B2tg	26–37	2·1	1·5	1·6	26·1	28·6	40·2	n.d.	Tr.	3·2	n.d.	n.d.	n.d.	7·9	7·3
	IIB3tg	37–46	4·5	4·6	3·0	27·6	24·6	35·7	n.d.	Tr.	4·9	0·6	21·9	97	7·9	7·4
5	Ap	0–10	5·7	5·8	4·1	34·0	29·3	21·2	1·2	—	n.d.	n.d.	n.d.	n.d.	5·7	4·8
	B1	10–16	7·4	4·7	4·4	34·7	28·1	20·8	0·6	—	n.d.	n.d.	n.d.	n.d.	6·3	5·7
	B2(g)	16–21	5·8	2·7	2·8	35·6	28·4	24·7	0·5	—	n.d.	n.d.	n.d.	n.d.	6·6	6·1
	IIB′1g	21–28	2·2	1·1	2·2	34·5	27·9	32·0	n.d.	—	n.d.	n.d.	n.d.	n.d.	6·9	6·2
	IIB′2(t)g	28–36	2·6	1·5	2·0	29·1	27·4	37·5	n.d.	—	n.d.	n.d.	n.d.	n.d.	7·1	6·4

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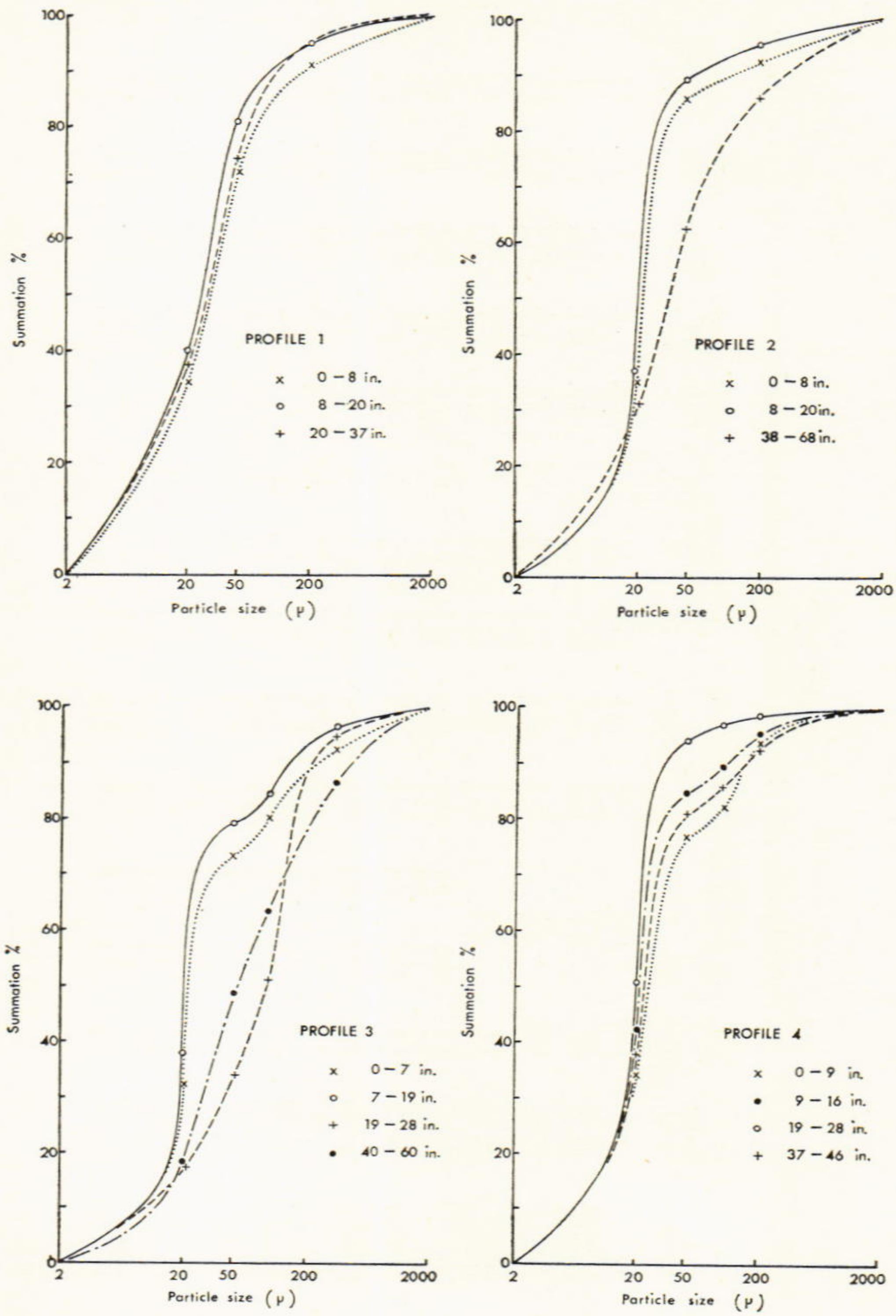

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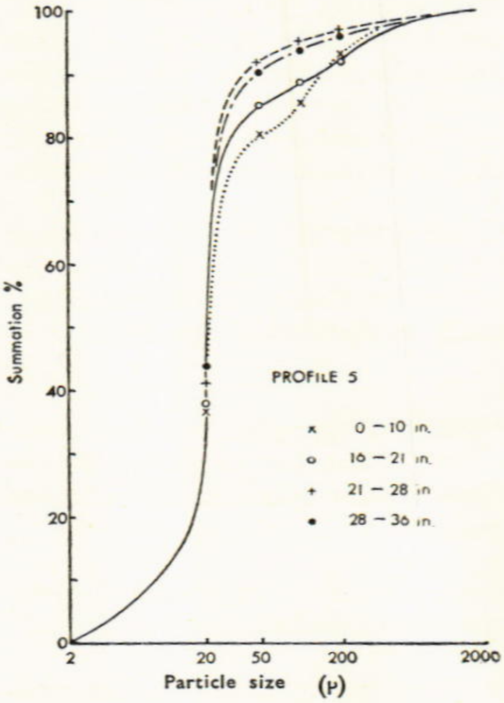

FIG. 5·3. Distribution of particles 2–2000 μ in soil horizons.

horizon. This undoubtedly reflects a lithological discontinuity, and not clay-translocation alone.

To help identify parent materials, the results were recalculated on a clay-free basis, and the distribution of sand and silt-size fractions plotted as summation curves (Fig. 5·3). The curves reveal no distinct lithological discontinuity in profile 1, but show definite variations in each of the other profiles. Samples from the nearly flint-free Bt horizon of profile 4 (19–28 in.) and the similarly textured lower horizons of profile 5 give similar curves, indicating the presence of well sorted loess-like material with a distribution peak in the coarse silt (20–50 μ) range. The Ap and B1t horizons of profiles 2 and 3, the Ap, Eb/Bt and B3t horizons of profile 4, and the Ap and B horizons of profile 5, also have many particles in this range, but frequency maxima are less well defined at the upper end, and curves for horizons from profiles 3, 4 and 5 show a bimodal distribution with a weak secondary maximum in the fine sand (100–200 μ) range, suggesting a loess mixed with more sandy material. Curves for profile 3 confirm a lithological discontinuity at the base of the B1 horizon, and show that the skeletal grains in the horizon below are mainly of fine sand. The lowest laminated horizon appears less well sorted, probably because thin depositional layers were mixed in sampling.

Chemical characteristics. Organic carbon, $CaCO_3$ equivalent, 'exchangeable hydrogen', 'free Fe_2O_3' (dithionite-extractable), cation-exchange capacity and pH were measured on selected horizons of the profiles described (Table 5·2). Organic carbon was determined by Tinsley's (1950) wet oxidation method; $CaCO_3$ equivalent by calcimeter (Bascomb, 1961)

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and dithionite-extractable Fe by a modification of Deb's (1950) method, shaking overnight at room temperature with sodium dithionite solution buffered at pH 3·8 by acetic acid and sodium acetate. 'Exchangeable hydrogen' was estimated by a method based on that of Mados (1943); cation-exchange capacity by Bascomb's (1964) barium/magnesium method; and pH in 1:2·5 water and 0·01 M $CaCl_2$ suspensions by glass electrode.

Free iron oxide. Contents of iron oxides extractable by dithionite range from 2·2 to 6·5% in profiles 2, 3 and 4, with most in the Clay-with-flints B horizons. As in *sols lessivés* generally, the free Fe_2O_3/clay ratio does not change greatly with depth and is usually rather less in the Bt than in horizons above.

Organic carbon. These profiles, sampled in inter-plot pathways, have around 1% organic carbon in Ap horizons, about the quantity in the no-manure plot, and more than 0·2% in sub-surface horizons. Profile 5 has most and may include topsoil from up-slope.

Calcium carbonate. Except in profile 5, outside the experimental plots, all surface horizons have small amounts of added chalk.

pH and base-saturation. In contrast to the analogous soils under semi-natural vegetation (Avery, 1964), all profiles except 5 are neutral or alkaline throughout, and base-saturation values for profiles 2, 3 and 4 exceed 90% to depths exceeding 40 in. These values indicate that the Broadbalk soil has been re-saturated to considerable depths, presumably by slow redistribution of added calcium by earthworm activity and soil-water movements, coupled with diffusion and cation-exchange.

Cation-exchange capacity. Ap horizons of profiles 2, 3 and 4 have cation-exchange capacities of 15–16 m.e./100 g. Values for the sub-surface horizons generally increase with clay content, but range from 43 to 64 m.e./100 g clay, indicating significant variations in the exchange properties, and presumably in the mineralogy, of the clay fractions. The horizons of profiles 3 and 4 developed in silty material have larger values in relation to their clay content (57–64 m.e./100 g clay) than those in Clay-with-flints.

Classification of representative profiles

The morphological and analytical data show that variants A–C (profiles 1–4) have a Bt horizon with evidence of gleying. In the system used by the Soil Survey of England and Wales, which resembles that used in France (Aubert, 1965), they are classified in a sub-group of *sols lessivés* with gleying (*sols lessivés hydromorphes*), within the major group of brown earths (*sols brunifiés*). Because profile 5 has no well defined Bt horizon, except as part of a buried soil, variant D is classified as an undifferentiated brown earth (*sol brun*) with gleying in the lower part.

In the earlier American classification (Thorp & Smith, 1949), variant C

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is evidently a grey-brown podzolic soil, whereas the dominant *Batcombe* variants (A and B) could be classed as red-yellow podzolic soils.

In the new U.S.D.A. classification (Soil Survey Staff, 1960; 1967), soils of humid regions with an argillic (Bt) horizon are divided between the Alfisol and Ultisol orders. Using current (1967) criteria, profiles 2 and 3, and presumably also profile 4, are Alfisols because the base saturation at 50 in. below the top of the argillic horizon exceeds 35%. Their morphology, and temperature and moisture regimes, place them in the sub-order of Udalfs. At the great group level, profile 2 (variant A) conforms to the provisional definition of Paleudalfs, comprising Udalfs that have thick argillic horizons with stronger chromas and redder hues than in Hapludalfs (typical grey-brown podzolic soils). The prefix *Pale* associates them with old ground surfaces, and implies that the B horizons may be relict formations. Profiles 3 and 4 are difficult to classify satisfactorily at this level because no allowance is made for the occurrence of lithological discontinuities in distinguishing Paleudalfs from Hapludalfs, and because the lower boundaries of the argillic horizons are ill-defined. On current definitions profile 3 could be a Hapludalf and profile 4 a Paleudalf, but these identifications are not consistent with the apparent genetic relationships of the soils.

An essential difference between the *Batcombe* profiles and profile 4 appears to lie in the fabric of the B horizons, which are bracketed as 'argillic' in the U.S.D.A. system. The brightly coloured Clay-with-flints B horizons in the former profiles have a predominantly sepic plasmic fabric with much moderately to strongly oriented clay, but with only a small proportion of identifiable argillans. In contrast, the brown B-horizon fabric in profile 4 has a predominantly asepic fabric with much less strongly oriented clay, most of which occurs as well defined argillans.

The Mineralogy of Broadbalk Soils

By A. H. Weir, J. A. Catt and E. C. Ormerod

Introduction and analytical methods. The mineralogy of Chiltern soils similar to those of Rothamsted Farm was first studied by Brown *et al.* (1956, 1957), Loveday (1958) and Avery *et al.* (1959). Stephen (1961) analysed the sand fractions from a profile in Broadbalk Wilderness, and Greene-Kelly (1954, 1956) studied clays from profiles in the Wilderness and surface soils of the arable plots. Weir & Ormerod (1968) described the clay mineralogy of surface soils from plots 3, 10 and 13 of Broadbalk sections IA, II, III and IV. However, the mineralogical composition of all the important size fractions from the various horizons of Broadbalk soils has never been published, and it is therefore necessary to fill in many of these details.

Samples from profiles 2, 3, 4 and 5 (see pp. 71–74), and surface soils (0–8 in.) from plots 3, 10, 13 and 15 of section II (sampled by the Chemistry

Soil phosphorus. There have been studies by:

1. Dean (1938) who used the Broadbalk soils for his pioneering work on the fractionation of soil phosphorus.
2. Aslyng (1954) illustrated his ideas on phosphate potentials in soils by analyses of the Broadbalk soils.
3. Nagelschmidt and Nixon (1944) used an X-ray diffraction technique to show that superphosphate applied as fertiliser reverted to apatite in soil.

Soil potassium. K studies on Broadbalk soils are more recent. They include work by Talibudeen & Dey (1968) on activity ratios, by Addiscott (in press) on quantity/intensity curves and the relationship of buffer capacity to K saturation of the cation exchange complex, and by Arnold (1962) on potassium potentials.

Other elements. Rickson's unpublished work done in 1948 on the fluorine content of the Broadbalk soils showed that, though plots treated with superphosphate contained slightly more F (mean 0·022% F) than the untreated plots (mean 0·017% F), the individual figures fluctuated considerably. However, much of the added F had been lost from the 0–9-in. layers. Though there was no relation between F content and pH of the soil, there was an indication that F content was related to $CaCO_3$ content.

Little (1953) used some of the soils in his study on readily soluble sulphates in soils.

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