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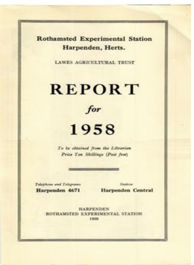

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SOME ASPECTS OF SOIL MINERALOGY

By

I. Stephen

According to Robinson (1949) " soil may be conveniently considered as being composed of a relatively inert framework of unweathered minerals, together with the so-called clay–humus complex, consisting mainly of the products of the chemical weathering of silicates and with humus, which is the product of the decay of plant and animal residues in the soil ". The mineral matter of soils consists of particles of all sizes which, for the purposes of describing the mechanical composition, are conventionally divided into four grades: coarse sand from 2 to 0·2 mm.; fine sand from 0·2 to 0·02 (or 0·05) mm.; silt from 0·02 (0·05) to 0·002 mm.; and clay below 0·002 mm. The sand and silt fractions may be ordinarily regarded as the " relatively inert framework ", while the clay is the more reactive part of the soil and is the main seat of the property of base-exchange as well as being largely responsible for the mechanical properties. Primary mineral grains, such as quartz, feldspars, micas, amphiboles, pyroxenes, iron oxides and various accessories, normally constitute the bulk of the sands and silts, although occasionally secondary products of weathering, including concretionary material, may be present. The clay fraction may contain grains of quartz and other resistant primary minerals, but most of it consists of material of secondary origin in the colloidal state which has been formed by the processes of weathering of primary minerals, either in the present environment or during previous cycles of weathering and sedimentation.

Methods for identifying the minerals in soils follow the lines normally used in studies in sedimentary petrography. Because of their amenability to study by the petrological microscope, the coarser material in soils received most attention by earlier workers in soil mineralogy, and much of that work was concerned with identifying the minerals in the fine sand fractions to correlate drifts with geological formations with a view to parent material classification (Hendrick and Ogg, 1916; Hendrick and Newlands, 1923, 1925; Hart, 1929a, b). The constitution of the clay fraction was largely ignored, because suitable techniques for its study were lacking. The applicability of X-ray diffraction to the problem of determining the constitution of fine-grained materials was demonstrated by Hadding (1923) and Rinne (1924), and using this method Hendricks and Fry (1930) and Kelley *et al.* (1931), working independently, showed that the colloidal fractions separated from some selected soils in the U.S.A. contained crystalline particles comparable with those of the layer lattice silicates montmorillonite–beidellite and halloysite. Since then much work has been done on the occurrence of clay minerals in soils, and other techniques employed for their characterization include differential thermal analyses, cation exchange reactions, electron microscopy and infra-red spectrometry.

Pedogenic weathering

Not many detailed studies have been made of the changes undergone by rocks and minerals in the course of disintegration and decomposition into clay. It is now realized that all the classical soil-forming factors (parent material, climate, time, topography and biotic agencies) have their influence on the processes of weathering, and consequently on the minerals present in soil colloids, and to assess the importance of the different factors the weathering products of different rock types must be compared under similar environments, and *vice versa*.

Several studies of rock weathering of this kind have been made at Rothamsted. One area studied was the Malvern Hills in the west of England, where the suite of rocks shows great variation from acidic rocks (granite) to highly basic rocks rich either in biotite (biotitite) or in hornblende (appinite): furthermore, there is no glacial or other drift to introduce ambiguities in the relationship of bedrock and soil (Stephen, 1952a, b). The mineralogical composition of the soils was determined by the constitution of the underlying rocks, both as regards the coarser " inherited " particles and the clays. In the sands, quartz and feldspar were the principal minerals in the granite-derived soils, whereas in the soils derived from the basic rocks amphiboles, epidote-clinozoisite and iron oxides occurred in fairly large amounts; the soil derived from the biotitite also contained characteristic yellowish brown glistening flakes of vermiculite. Illite (dioctahedral mica) * was dominant in the clays of the granite-derived soils, and trioctahedral chlorite–vermiculite in those derived from the basic rocks; the presence of these minerals was directly related to the trend of alteration of the primary minerals in the different rock types. The illite appears to be derived exclusively from the breakdown of feldspar in which abundant white mica is developed as hydrothermal inclusions. The operation of the weathering sequence (biotite, hornblende) ⟶ chlorite ⟶ vermiculite appears to be the conditioning factor leading to the development of the soil clays derived from the basic rocks. Pseudomorphing of original biotite by chlorite in the biotitite, and the development of finely crystalline secondary chlorite at the expense of hornblende in the appinite, was observed in thin sections of the weathered rocks, and further weathering of the chlorite from either source through intermediate stages of mixed chlorite–vermiculite produces vermiculite in the soils. The occurrence in the clays of illite and chlorite, which are early members of the layer lattice silicates in the sequence of weathering proposed by Jackson *et al.* (1948), and the presence of much unweathered (though readily weatherable) minerals in the sand fractions, leads to the conclusion that the soils are at an early stage of development.

The association of acid and basic rocks, as described above, is

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* The terms tri- and dioctahedral were proposed by Stevens (1946), the former to designate layer lattice minerals in which all three octahedral positions are occupied, and the latter for those in which one in three octahedral positions is vacant.

common in many regions of igneous intrusion and metamorphism, and a comparative study of two profiles from Ghana, occurring only a few miles apart under similar environments, on two such contrasted rock types (a feldspar–quartz–schist and a hornblende–garnet–gneiss) has shown that, even under the more extreme climatic conditions there, the nature of the parent rock was strongly reflected in the constitution and also the morphology of the derived soils (Stephen, 1953). The acid schist gives a grey quartzose sandy soil containing kaolin–montmorillonite clay, whereas the soil derived from the basic gneiss has the characteristics of a typical tropical black earth (regur) with almost exclusively montmorillonite clay. The more complete weathering of the soils, compared with those on the Malvern Hills, is indicated by the lack of ferromagnesian minerals (amphiboles, pyroxenes) and feldspars in the surface horizons, although these are abundant constituents of the parent rocks.

The degree of crystallinity of rocks may also affect the products of weathering (Muir, 1951). In a soil developed from a holocrystalline olivine-basalt in Syria, the clay was dominantly kaolin, whereas a merocrystalline olivine-basalt with over 70 per cent glass in the ground mass altered to montmorillonite. The two also differed in chemical composition, particularly in the Ca/Mg and Ca/Sr ratios in their exchange-complex.

The probability of drainage conditions influencing the clay minerals in soils was indicated by Nagelschmidt *et al.* (1940), working on Indian soils, and the combined influence of drainage and parent material has been established by Mitchell (1955) for some Scottish soils. Soils developed on drift derived from granite and various metamorphic and sedimentary rocks (quartz–schist, quartzite, Dalradian slates, Old Red Sandstone, etc.) contain illite as the major clay mineral, whereas in those developed on drift from basic igneous source rocks vermiculite or montmorillonite is dominant. The influence of drainage is pronounced in these latter soils, vermiculite tending to prevail in the brown earths with free drainage, and montmorillonite in the gley soils. The same relationship between the production of vermiculite or montmorillonite and drainage conditions in soils derived from basic rocks was also reported by Butler (1953) for soils overlying serpentine in the Lizard area of Cornwall, and by McAleese and Mitchell (1958) for soils derived from basaltic parent material in Northern Ireland.

The great influence of the parent material on the products of weathering is evident in the studies mentioned above, which are mainly confined to temperate regions; but where weathering is intense and prolonged, as under tropical and subtropical conditions, its influence may be greatly lessened or even eliminated. For example, in some parts of Tanganyika, where wet and dry seasons with high temperatures alternate, both acid and basic gneisses give rise to red earths with dominantly kaolinitic clays (Anderson, 1957; Muir *et al.*, 1957). Except where these soils are shallow, only minor amounts of feldspars, ferromagnesian and other primary minerals are present, and it appears that they weather directly to kaolinite, mica and iron oxides; consequently, as stated by Muir *et al.*, " it is only by an examination of the resistant heavy minerals that an indication of the probable source rocks is obtained ".

Weathering of individual minerals has been much studied; much of this work has concerned the micas, as, in addition to being widely distributed in soils, they are potential sources of potassium available to plants. From these studies the process of vermiculitization in the weathering of primary biotite (trioctahedral mica) appears to be common. The vermiculite is formed either *via* mixed-layer biotite–vermiculite intermediate products (Wager, 1945; Walker, 1949; Butler, 1953, 1954) or *via* mixed-layer biotite–chlorite and chlorite–vermiculite products (Stephen, 1952a; Butler, 1953). The most pronounced chemical changes occurring during the weathering of biotite to the expanded-lattice mineral are: loss of potash and magnesia, gain of silica and water, almost complete oxidation of iron and a large increase in cation-exchange capacity. Fewer studies have been made on the weathering of the dioctahedral mica muscovite. A comparative study of muscovite from adamellite and the overlying soil in Cornwall showed that, although structural changes were slight and flakes from both environments gave visually identical X-ray patterns, the loss on ignition from the soil muscovite was greater than from the fresh mineral, and the potash content had decreased (Butler, 1953). The excess of water and deficiency in potash in hydrous micas compared with normal micas can be explained on the basis of substitution of oxonium ions (H_3O^+) for potassium in the interlayer positions (Brown and Norrish, 1952).

The occurrence of a mineral which appears to be the dioctahedral analogue of vermiculite was described by Brown (1953, 1954a) in the clays of some gleyed soils developed on Carboniferous till in Lancashire. It is apparently the weathering product of an aluminous mica, as it is dominant in the upper more highly weathered layers, where it replaces dioctahedral hydrous mica, the chief clay component in the lower layers. A similar antipathetic relation with depth between mica and vermiculite occurs in some soils from Anglesey (Muir, 1958), e.g., in the Treuddyn series, a brown earth of low base status developed in drift of Millstone Grit and Mona Complex origin, and in the Dyfnan series, a non-calcareous gley soil derived from drift from Carboniferous shale and limestone.

	% K_2O in clay	% mica in clay	% vermiculite in clay
Treuddyn series			
0–5 inches	1·59	20	45
28–36 inches	4·34	65	Nil
Dyfnan series			
0–7 inches	0·70	Trace	75
14–23 inches	2·71	60	15

The increase in vermiculite at the expense of mica in the surface horizons, together with a decrease in the potash content, suggests that the vermiculite originates by loss of potassium from the mica.

That the degree of alteration of the mica lattice may be important in agronomic practices has been demonstrated by Brown (1954b) for some Irish soil clays. The clay minerals present in the soils were illite (mica), vermiculite, chlorite, kaolin and a material provisionally called " degrading illite ". All the soils that, in field experiments, fix potash contained " degrading illite ", whereas the others did not, and the " degrading illite " may either fix potassium or be related to the actual cause of fixation.

Study of the detrital minerals

The mineralogical examination of the sands and silts is greatly facilitated by dividing them into fractions according to specific gravity. This is done by separation in a liquid of high specific gravity, e.g., bromoform (S.G. 2.90). The heavy fraction (S.G. $>$ 2.90) includes the ferromagnesian and related minerals, iron oxides, and various stable accessory minerals such as zircon, tourmaline, rutile, anatase and garnet. Although in immature soils derived from igneous and metamorphic rocks rich in ferromagnesian minerals the amount of " heavy residue " may be 50 per cent or greater, in sediments and derived soils it is often less than 1 per cent, but may contain a wide variety of mineral species, 15–20 being common. These minerals are particularly suitable for purposes of correlation and differentiation, because distinctive associations of minerals are characteristic of different rock types and stratigraphic units. Undoubtedly the most important roles of heavy mineral analyses in pedological studies are in determining the sedentary nature (or otherwise) and the degree of uniformity of the materials comprising the solum, and thus in deciding how far vertical variations reflect pedogenic processes or are geologic in character caused by parent material or depositional differences.

Often a cursory examination of the residues will determine whether or not a soil is derived *in toto* from the underlying formation, as shown by Stephen *et al.* (1956) in a study of tropical black clays with gilgai in Kenya. The soils occur on the Athi Plains to the east of Nairobi, and are underlain by volcanic rocks of trachytic affinities. On the east the plains are bounded by hills of Basement Complex, which contains a wide variety of metamorphic rock types. An examination of the heavy residues of the sands from the soils showed that they could not be entirely derived from the underlying volcanic rocks, as minerals occurring in the lavas and species such as sillimanite, kyanite and staurolite were present in all horizons. The latter are characteristic of metamorphic rocks, and their presence suggested that Basement Complex material had been deposited on the soils possibly by wind transportation during dry Interpluvial periods. These additions then became incorporated in the soils by the churning action resulting from their shrinking and cracking properties.

Studies of " chalk heath " soils on the South Downs and of soils overlying serpentine in Cornwall by Perrin (1956) and Coombe and Frost (1956), respectively, showed that the mineralogical composition of the soils is inconsistent with derivation from the underlying rocks. On the basis of particle-size distribution analyses, they postulated substantial loessial accessions to the soils. Perrin further points out that deposits of a well-graded nature with a maximum particle-size distribution in the silt grade (0·04–0·03 mm.), also considered to be loess-like in character, occur overlying Chalk on the Berkshire Downs, the Carboniferous limestone in Derbyshire and the Clay-with-flints on the Chilterns. Where undisturbed by recent erosion, the superficial layers of both plateau and valley drifts on

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the Chilterns are rich in silt and overlie more clayey subsoil horizons; the non-clay fraction of these subsoil horizons may also be considerably coarser in texture than in the surface layers (Avery, 1958). Although the silty character of the surface soils and the increased clay content of the subsoil could be attributed to pedogenic processes—such as the physical disintegration of sand grains *in situ* to yield silt-sized particles by a mechanism such as frost shattering combined with clay-eluviation from or clay-decomposition in the A-horizons—mineralogical studies indicate that parent material differences are also involved (Stephen, 1957; Loveday, 1958). Soils studied in detail included profiles of the Batcombe series, as mapped by the Soil Survey of England and Wales, which is developed over Clay-with-flints that probably consists largely of the weathered remains of Chalk and Eocene sediments redistributed by ice-action or solifluxion. In these profiles, occurring on level or gently sloping plateau sites where the drift is thick, thin sections show that some physical disintegration of sand grains has taken place and also provide evidence of clay migration and deposition in the heavier-textured B-horizons. In all the profiles studied, however, the coarse silt (0·05–0·02 mm.), and, to a lesser extent, the fine sand (0·2–0·05 mm.) of the surface layers contain heavy residues of a different mineralogical character, and therefore different origin, from that of the subsoil horizons. Non-opaque heavy minerals common to all horizons are zircon, rutile, tourmaline, kyanite and staurolite, but the surface horizons contain a more varied suite, including epidote-clinozoisite, garnet, chlorite and green hornblende, which are rare or absent in the substrata. The mineralogical evidence in conjunction with particle-size distribution studies strongly suggests a loessial origin for a major portion of the silt, and the added wind-blown materials seem to have been incorporated with the underlying drift by solifluxion either during or after their deposition. These profiles have therefore developed in materials of different geologic origin and character and the pedogenic processes have further accentuated the differences.

As well as the fairly widely separated loess-like deposits discussed above, undoubted loess of considerable thickness at Pegwell Bay in Kent has been described by Pitcher, Shearman and Pugh (1954). Such deposits may, therefore, be more widespread than was formerly supposed and they may constitute or contribute to the upper layers of soils over considerable areas in Southern England. One of the areas at present being investigated is the Mendip Hills in Somerset, where it is uncertain whether the soils overlying the Carboniferous limestone are residual or whether they are partly derived from superficial deposits of different origin. These soils have maximum particle-size distributions in the range 0·06–0·02 mm., which has led to the suggestion that they have developed in part in a loessial cover overlying the limestone (Findlay and Clayden, 1958). The insoluble residues from the limestones, however, have a very similar mechanical composition, so it appears that the resolution of the problem will depend on mineralogical evidence, using criteria similar to those advocated by Smithson (1953) to recognise residual soils on Carboniferous limestone in North Wales. After a mineralogical examination of the residues from the limestone the criteria suggested were that the light fraction of the soils should be dominated by quartz euhedra and chert rather than detrital quartz grains, and that the heavy fraction should be small in amount and poor in mineral species. The cover in North Wales is strongly influenced by mixed drift of northern origin, and the limestone may have contributed little to the constitution of the overlying soils but acts rather as " a foster-parent that has imparted to the profile the characteristics of a limestone soil ".

Although normally constituting 95 per cent or more of the sands and silts of soils, the light minerals (S.G. $< 2 \cdot 90$) do not usually receive as much attention as the heavy minerals. In many soils the light fraction is dominated by quartz and contains only few other mineral species, thus making the assemblages less valuable than the heavy residues for purposes of correlation. A study of the light minerals, however, should not be neglected, as the separates often possess features worth attention. Various forms of silica occurring in soils have been described by Smithson (1956), who, besides drawing attention to varieties of quartz and chalcedony, described and depicted characteristically shaped grains of opaline silica occurring in the silts of various British soils. These originate from organic matter, being components of grass leaves, and he suggested that a study of such phytoliths might provide information about the former vegetation and soil conditions of the sites where they occur. Phytoliths derived from *Nardus stricta* have unmistakably characteristic forms, but the shapes of others can only be assigned to tribes of grasses (Smithson, 1958). The presence of phytoliths in palaeosols in Illinois has been noted by Beavers and Stephen (1958), indicating the possibility that they could be used to determine the presence and location of buried A-horizons. The opal phytoliths in some of the palaeosols had been transformed to chalcedony.

An unusual form of chalcedony in soils developed on Clay-with-flints and allied deposits has been reported by Brown and Ollier (1957). The grains, apparently of inorganic origin, occur in a variety of forms ranging from bundles of parallel rods arranged in tabular form to grains with a botryoidal or honeycombed appearance. As silica is considered to be more mobile under tropical conditions, a warmer climate of the past may have promoted their formation. Some support for this hypothesis is given by a consideration of the morphology of the plateau drifts (Avery, 1958). A characteristic feature of these is the incorporation of " relic " soil materials of a braunlehm character with red mottling (rubefication), which according to Kubiëna (1956) occurs in strongly alternating wet–dry regimes of the tropics.

Feldspars also occur in the light fractions of all but the most highly weathered soils and, as specific types of feldspar are typical of different groups of igneous and metamorphic rocks, a study of the variety present may be useful in determining the source of soil materials derived from such rocks (e.g., Muir and Stephen, 1957). As sodic plagioclases are more resistant to weathering than the calcic plagioclases, Graham (1949) has suggested that the Na/Ca ratios of the sands and silts could be used to assess the degree of weathering undergone by soils; and Hawkins and Graham (1950), studying silt separates from the A-horizons of some Missouri soils, showed that the percentages of potash feldspar and plagioclase were in direct proportion to the fertility levels measured by field tests. The relation between the feldspar content and the agronomic potential of soils has also been demonstrated by other workers (e.g., Leenheer, 1950a, b; Jeffries *et al.*, 1953; Jeffries *et al.*, 1956). Other minerals that frequently occur in the light separates are weathered micas, glauconite, calcite and gypsum; these are diagnostic of either derivation from particular types of source rocks or of characteristic weathering regimes.

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