

that I have urged repeatedly; and the theory may be restated by way of a summary of the preceding paper.

In *Lovenia forbesi* (or any other Echinoid), persistent development of new plates from the ocular margin causes a downward (orad) gliding of the columns. If no structure is developed to interfere with this procession, the older plates become gradually resorbed at the peristome margin, or all gradually and uniformly decrease in size as they increase in numbers. If, however, some special character is assumed by a series of plates in a column (whether ambulacral or interambulacral), and this character, for reasons of function, must be maintained in a definite position in the test (e.g. the large adoral plates of the interambulacra in *Lovenia* or the ambulacral processes of the perignathic girdle in a *Diademoid*), the oncoming plates of the column become congested against the barrier thus formed. Under such circumstances the plates become lessened in height and restricted in width, forming demi-plates, and often coalescing to form compound plates. Plate-crushing is first developed, both ontogenetically and phylogenetically, at the line of contact between the moving column and the barrier.

The resulting structure may be adapted subsequently for special functions (e.g. phyllodes, 'prehensile' petals, or consolidation of the test fabric), but in its origin it is purely a mechanical outcome of the growth of the Echinoid test.

III.—THE APPLICATION OF PETROLOGICAL AND QUANTITATIVE METHODS TO STRATIGRAPHY.

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I. INTRODUCTION.

ON account of the aid it has given, palæontology has been termed the handmaiden of stratigraphy, but up to the present time petrology has not been called upon, so far as it might have been, to fulfil its appropriate duty towards the elucidation of the problems of stratigraphical geology and palæogeography.

The lithology of sediments has been studied very largely in the field, but is still in its qualitative stage. Systematic quantitative work has hardly been attempted. Used in conjunction with palæontology the broad study has proved of great value in determining facies, and in yielding clues to the disposition of land and water and their relative changes in past geological times. The fragments contained in the coarser rocks, such as breccias, conglomerates, greywackes, grits, etc., have been used to some extent petrologically as giving an indication of direction and distance of source, but the finer detrital minerals of sands, clays, limestones, marls, etc., have not yet been adequately studied with the same view. Our ultimate aim must be the knowledge of the exact mineral composition of every sedimentary rock in the geological column. In such a way only can the economic resources of our sediments become familiar, the exact conditions of deposit known, and the lesser features of palæogeography realized.

II. PETROLOGICAL METHODS.

The usual petrological methods of treating sediments by panning, and the use of heavy liquids, divide samples into two important and convenient crops of densities respectively above and below a mean of about 2.8. Of the liquids in common use, bromoform, when it can be obtained, appears to be most convenient. Operations with it are clean, and, what is of great importance when hundreds of samples are being examined, very rapid, the time taken in washing with benzene, and drying, being a minimum. Its mobility is a valuable asset, but has given rise to the objection that separations are rendered less complete on account of convection currents which are set up in it by slight differences in temperature. If necessary, care can be taken to avoid these, and in the writer's experience separation is quite as good, if not better, than with the more viscous aqueous heavy solutions, where the process takes longer and the grains move less freely. The only real objection to the use of bromoform is its loss by evaporation during separation, and while the washings (in benzene) are being concentrated. Theoretically, bromoform may be used over and over again without end, but practically there is a slow and steady loss. This may be obviated to some extent by the use of separating funnels stoppered at the top, but they are usually too small to accommodate a sufficiently large quantity of sediment, the sand, etc., tends to hang round the sides, and the subsequent washing is often troublesome. An ordinary funnel fitted with a glass stopper or a rubber tube and clip leaves little to be desired; but with bromoform a large surface of liquid is exposed to evaporation. The funnel may therefore be covered by a clock glass. Mercury potassium iodide is the most suitable of aqueous solutions, crystallizing out less rapidly and being less viscous than Klein's solution (cadmium boro-tungstate). It is very poisonous and has a corrosive action upon the skin, but these objections are not serious with clean working, for the liquid need not be touched. It should, however, be kept from air, and in contact with a little mercury. While not as convenient as bromoform, for it is less mobile, and necessitates washing with water, and consequent loss of time in washing and drying, it is the best substitute when that liquid is procurable with difficulty (as in 1914-15). It may be quickly prepared in the laboratory from mercuric and potassium iodides, and, like other aqueous solutions, may be used and recovered repeatedly without appreciable loss. For the further separation of the heavy crop (> 2.8) methylene iodide, of density about 3.33, is very convenient. The sediment is washed with benzene and the separation is therefore rapid. Its expense is an objection, but small quantities only need be employed for the (usually small) heavy crops.

The portion of density > 2.8 contains the heavy detrital minerals which are of greatest interest, beauty, and value from a stratigraphical point of view. Further separations may be made from this crop by electromagnetic and electrostatic methods, by the use of heavier liquids, and by hand-picking.

Apart from the included rock-fragments and compound grains, sediments exhibit considerable variation in petrology. Most of the

constituent minerals are allogenic. In the authigenic group occur glauconite, hæmatite, limonite, marcasite, opal, chalcedony, and other forms of secondary silica, calcite, dolomite, gypsum, barytes, etc. The cementing materials of rocks come under this head, as do also those minerals such as limonite, anatase, leucoxene, secondary silica, micaceous aggregates, etc., when they result from the decomposition in situ of other minerals. It is not certain to what extent these secondary minerals are also detrital, for they may have been themselves derived as a result of previous decomposition of rocks. Anatase has been frequently observed growing upon, and at the expense of, ilmenite and leucoxene.¹ The opinion has been expressed that the tabular form is probably always authigenic, but that the pyramidal form may be allogenic. Among the few deposits known to the writer in which anatase is really plentiful in fairly large crystals (grains .3 mm. diameter) is the Pliocene (?) sand of St. Keverne, near the Lizard, Cornwall. The sand is full of ilmenite (decomposing to leucoxene) derived from the Lizard gabbro, and there is little doubt that the blue tabular anatase is a secondary product from ilmenite. In the Yeovil sands (Inferior Oolite) abundant yellow tablets of anatase accompany the yellow and red rutile which makes up a large part of the non-magnetic residue. Koenigsberger describes rutile pseudomorphs after anatase in the Eastern Aar mass,² and the unexplained abundance of rutile in many sediments indicates that much work remains to be done upon these isomers.

Glauconite may be detrital in certain cases. Dr. A. Morley Davies holds the view, with which the writer agrees, that the glauconite of some of the Mesozoic and Cainozoic deposits was derived from older beds and was not formed at the same time as the sediment. In that case redeposition probably took place under similar (i.e. reducing) conditions to those of its formation. Certainly much of the glauconite of deposits of all ages from Cambrian to Pliocene has no suggestion of foraminiferal character about the grains.

Side by side with the mineral analyses of the deposits, mechanical analyses, obtained by elutriation, should also be made. A good classification is that suggested by Mr. T. Crook: gravel 10 to 1 mm., sand 1 to .1 mm., silt (or very fine sand) .1 to .01 mm., and mud less than .01 mm. diameter. The material is, for practical purposes, sifted to 1 mm., and the mud or true clay portion estimated by difference in the elutriation with the form of apparatus he recommends.³ If necessary, intermediate grades can be estimated and inserted later in the tables, which are not invalidated if sufficient grades had not been estimated previously. In sands (e.g. for glass-making, etc.), it is often desirable to know the percentage weights of the portions of diameter > .5 mm. and < 1 mm. (coarse sand), > .25 mm. and < .5 mm. (medium sand), and > .1 mm. and < .25 mm. (fine sand); these can be

¹ J. B. Scrivenor, *Min. Mag.*, vol. xiii, p. 348, 1903; H. H. Thomas, *Q.J.G.S.*, vol. lxx, p. 232, 1909; W. R. Smellie, *Trans. Geol. Soc. Glasgow*, vol. xiv, p. 267, 1911-12.

² *Economic Geology*, vol. vii, p. 697, etc., 1912.

³ Hatch & Rastall, *Sedimentary Rocks* (London, 1913); Appendix by T. Crook, p. 350.

obtained, if required, by treatment with circular-holed sieves, but separation below .5 mm. by sifting is hardly satisfactory.

A more detailed classification, such as the following, has then been found useful, and may be carried out with adaptations of the Schoene apparatus.

	Diameter in mm.	
Fine gravel	> 1	
Coarse sand	> .5 and < 1	} Sand grade.
Medium sand	> .25 and < .5	
Fine sand	> .1 and < .25	
Superfine sand (or coarse silt)	> .05 and < .1	} Silt grade.
Fine silt	> .01 and < .05	
Clay	< .01	Mud grade.

The mud grade may be divided, if desired, into portions of diameter greater and less than .005 mm.

In sediments the portion of diameter between 1 mm. and .01 mm. is found to be most amenable to treatment for heavy residues; that over 1 mm. diameter frequently contains compound grains, and consists of the lighter minerals, while that below .01 mm. diameter, being a mud grade, tends to clog the heavy liquids during separation. During deposition (as during elutriation—the reverse process) the final velocities attained by small grains are dependent upon their surface areas (and therefore their diameters) and shape, rather than upon their densities. Nevertheless, as a result of greater density, it is found that the heavy detrital grains in any sediment often have an average diameter less than that of the lighter constituents. Minerals like mica, which have an excellent cleavage and therefore tend to occur in thin plates with a large flat surface, settle down slowly, and have, in spite of their greater density, a greater diameter than that of the accompanying quartz and felspar. Probably a constant ratio exists between the surface area (and also volume, for the thickness probably varies with the diameter) and that of the other grains, both of light and heavy minerals. As a result of measurement of material from various British sedimentary rocks, it is concluded that the volume of each muscovite grain is usually rather less than that of the average grain of quartz and felspar (perhaps about 80 per cent), but that the diameter of the flakes varies from two to four times that of the other heavy minerals. (The thickness of the mica flakes has been measured by focussing methods and birefringence.) The following are a few actual examples, selected from a large number:—

	Diameter in mm.	
	Muscovite.	Other heavy detrital minerals.
Bunter pebble-bed, Devon (Dr. H. H. Thomas)	.5	.2 to .3
Yeovil Sands . . . . .	.25	.06
Lower Greensand, Hunstanton . . . . .	.6	.25
Thanet Beds, Bramford . . . . .	.15	.04
London Clay, Holbrook . . . . .	.2	.08
Claygate Beds . . . . .	.15	.05
Boxstones (Crag) . . . . .	.5 to .6	.2
Lenham Beds . . . . .	.4	.2

Elutriation methods depend upon the final velocities of subsidence

of quartz.¹ It is clear that each grade obtained by elutriation will contain a proportion of heavy grains which from their diameter ought to belong to a smaller grade. If the percentage of material greater than 28 in density were a considerable one, the method of grading would be vitiated. Apart from the occasional cases where quantities of such authigenic minerals as limonite, pyrite, and pyrrhotite, etc., are introduced (and these may be extracted early in the operations), the heavy crop reaches only 4 per cent by weight in special cases. The average found by the writer after numerous separations of rocks of all ages is about .6 per cent. It is often, especially in coarser sands and sandstones, much less. Fine sands consisting largely of grains .2 to .05 mm. diameter, such as many of the samples of Bagshot Sands, appear to yield the largest residue (up to 4 per cent).² The earliest systematic work in this country on heavy detrital minerals appears to have been carried out by Allan Dick, and he was fortunate in choosing for his work Bagshot Sand from Hampstead Heath, which yields a large crop. Sands of diameter 2 to .5 mm. (e.g. Red Crag, etc.) yield a much smaller proportion of heavy minerals.

III. THE POSSIBILITIES AND LIMITATIONS OF THE METHODS.

A knowledge of the mechanical analyses of all the British incoherent sediments is economically valuable as well as of considerable geological importance. Our resources are not at present accurately known, but soil-analysts, authorities on water-supply and filtration, brick and pottery manufacturers, glass manufacturers, and workers in various branches of the engineering trades, particularly in the foundries, agree upon the importance of the data. From the purely geological point of view, many interesting deductions can be made regarding conditions of deposit, velocity of rivers and currents, and direction of drainage. We need, however, much more experimental work like that inaugurated in this country by Forbes, Sorby, and others, and carried on abroad, particularly in Germany and the United States,³ in properly equipped laboratories. The experimental work is largely synthetic, and seeks to build up deposits under certain known conditions; the corresponding analytical work upon geological deposits has rather tended to lag behind the synthetic—a result not expected in petrology. When sufficient data have accumulated it should be possible to devise schemes for graphical representation of sedimentary rocks, similar to those in use for igneous rocks. Diagrams might be used upon maps, and being placed at certain points over an outcrop, yield at a glance information as to heteropic or isopic formations, lithological changes, presence of shore-lines, etc.

But not only should deposits actually mapped at the surface be so treated. Specimens from wells, water- and trial-borings should be carefully preserved and subjected to analysis. It is a matter of

¹ R. H. Richards, *Ore-Dressing*, 1906, tables in Appendix.

² Exclusive of such local sands, etc., such as those bordering the granite masses of Devon and Cornwall. These sands may be full of tourmaline, etc.

³ See, for example, the recently published Professional Paper 86, U.S.G.S., "The Transportation of Débris by Running Water" (G. K. Gilbert).

great regret that tens of thousands of borings should have been made and so little of the material met with preserved. For mechanical analyses only 10 to 20 grams of the deposit are required, and for mineral analyses about a kilogram. It is to be hoped that this work will be developed in future. The drawing of sub-formational contour-lines has already proved of great value in water-supply questions, and in work upon concealed coalfields.¹ Combined with the isopachytes (lines joining points of equal thickness²) of super-imposed beds, these contour-lines yield valuable information as to the date and trend of folds and faults and the extension of deposits underground. But it is also necessary to know the lithological variations of the buried strata, and if contour-like grade-lines are also to be plotted upon maps, and compared with isopachytes and sub-formational contours, our basis of work on underground deposits must be quantitative. If from the graphical representation of sediments (preferably from curves) we can devise a scheme which represents by a number the average mechanical composition of a rock, we shall, by plotting these numbers referring to 'grades' upon a map, and drawing 'contour-lines', possess a valuable method of indication, not only of thicknesses of beds (by isopachytes), and of the form of the surfaces of concealed beds (by contours referred to Ordinance datum), but also of changes in lithology, the proximity of axes of unrest, etc., in rocks now buried deeply. Such information cannot fail to be of considerable economical value, and its academic interest is as great. In questions of water-supply much time and money will be saved if the thicknesses and exact mechanical composition (and therefore the permeability and filtering value) of the various members of the overburden with respect to the water-bearing stratum are known.³

Not only the mechanical composition, but the mineral constitution also, of each bed occurring in a boring, should be worked out. Evidence of unconformity between rock-series is thus accentuated and may be of value where fossil evidence is lacking or the relations of the beds obscure in the small core of the boring. It may be serviceable in certain areas, for example, to regard the change of mineral composition which usually exists, as the dividing line between the Permian and Triassic systems. The proximity of masses of crystalline rocks, of igneous bosses, etc., or even areas of ancient sediments forming old land-areas, may be revealed from borings as a result of the study of detrital minerals of the sediments bordering such land-areas. Additional information may be gained regarding

¹ Since the above was written Professor W. G. Fearnside has read a paper before the British Association upon the Underground Contours of the Barnsley Seam (*GEOL. MAG.*, October, 1915, p. 465). See also "The Use of Thickness Contours in the Valuation of Lenticular Coal Beds" (G. S. Rogers and C. E. Leshner): *Econ. Geology*, vol. ix, p. 707, 1914.

² Professor E. Hull used the term isodiametric (or isometric) lines, as those joining points of equal thickness of a formation *before denudation* had acted upon it. See *Q.J.G.S.*, vol. xviii, p. 127, 1862.

³ C. S. Slichter, "Motions of Underground Water": Water Supply and Irrigation Papers, No. 62, U.S.G.S. Hazen's 'Uniformity Coefficient' obtained by sifting is not satisfactory, and is applicable only to coarse deposits.

the position and extent of old shore-lines, and in the development of concealed coalfields, especially on outer ground where borings are as yet scarce, indications of the possible projection of pre-Carboniferous rock masses through the workable measures must be of great value. The information obtained by a petrological study of the sediments will thus be combined with that resulting from work on the mechanical composition, and with the analysis of records of borings and their cartographical expression in the form of isopachyte systems and sub-surface contours. If the results obtained actually fall short of the above ideal, the method will still be justified. A few years ago Professor W. W. Watts wrote in his suggestive Presidential Address to the Geological Society (1911): "In order to obtain what Dr. Marr has called the 'geogram' of a formation in its greatest perfection, we require to know the entire extent of its variations, not only along its outcrop, but in that part which is hidden from sight." The whole of the section ought to be quoted, if space permitted, in this connexion. The methods of work detailed above help considerably towards the perfect conception of the 'geogram' of a formation.

(To be continued.)

IV.—THE FLUVIO-GLACIAL GRAVELS OF THE THAMES VALLEY.

By R. M. DEELEY, M. Inst.C.E., F.G.S.

(Concluded from the February Number, p. 64.)

AT about 55 miles we reach the Hendon Lobe fan. At Dollis Hill the base of the fluvio-glacial beds lies at a height of about 200 feet, whilst their upper limit at Hendon is about 280 feet. On Finchley Hill to the north-east the Boulder-clay lies between the levels of 240 and 340 feet. This was a small lobe, and the fluvio-glacial fan may have sloped rapidly towards the fluvio-glacial gravels of the main stream. On the section, Fig. 2, the heights are shown without correction for slope towards the River Thames.

Where the Lea and Roding Valleys join the Thames Valley, and to the east as far as Hornchurch, the ice reached the fluvio-glacial gravels of the Thames. West of Woodford, at 43 miles, gravel caps the watershed between the Lea and Roding. Here the height of the deposit varies from 200 to 210 feet.

That the Boulder-clay should occur here as low as 80 feet above O.D. is very interesting, for it shows that, as at St. Albans, the fluvio-glacial gravels must have been piled against the ice face and buried its end in places. Indeed, as the lower Thames is reached the evidence favours the assumption that in pre-Chalky Boulder-clay time the valley was perhaps within about 80 feet of its present depth, and was subsequently filled with a deep mass of fluvio-glacial gravel, a view, as previously stated, held by Pocock.

At Dartford Heath, 22 miles, the gravel is from 90 to 140 feet above O.D. The upper portion of this deposit looks like a schotter formed by braided streams; but the lower portion is a clean current-bedded gravel and sand, such as an ordinary river might form.

The fossiliferous gravel at Greenhithe and Swanscombe, like the Dartford Heath deposit, lies within the upper and lower limits of