pietre verdi with each other; their stratiform, if not actually stratified, character in relation to the sedimentary rocks, and their frequent wedges and lenticular intercalations in the latter—all these phenomena on a large scale still present an intricate problem to which I shall refer in the descriptive sequel of the present paper.¹ The problem of the age of the pietre verdi in relation to the older rocks is, of course, rendered more difficult by the obliteration in the latter of organic remains through the ceaseless action of metamorphism past and present, or, in the words of Gastaldi: “while Nature gives us on this Earth myriads of living species, she with relentless hand destroys all trace of former life below.”

(To be concluded in our next number.)

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

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(Concluded from March Number, p. 111.)

ALTHOUGH detrital mineral work is as yet in its infancy, sufficient has been accomplished to show that we may look to it with success for indications of changes of drainage direction, evidences of denudation by reversal of the order of respective mineral assemblages from a sequence of rocks,² and generally for information regarding details of palæogeography. Professor A. de Lapparent referred to Professor L. Cayeux's work as proving the proximity of land, composed of primary rocks, to Lille in Landénian times.³ Dr. H. H. Thomas was able to demonstrate the change in source, and therefore in direction of drainage, of the river-borne heavy minerals in the Bunter sandstones of South Devon,⁴ the occurrence of garnets and staurolite being especially significant. Dr. T. O. Bosworth, in some preliminary work upon the detrital minerals of the Carboniferous Sandstone of the Midland Valley of Scotland, was led to the conclusion, partly by the respective presence and absence of garnets, that the beds could be divided into a series of great lenticular masses of sediment introduced from directions varying from north and north-west to north-east, east, and south.⁵ Mr. W. R. Smellie has discussed in rather more detail the origin of the minerals in the Upper Red Barren Measures of the Glasgow Basin, the drainage having been from the west or north-west.⁶ As a result of the study of the Tertiary sediments of East Anglia, the writer has been able to prove that the

¹ Professor Bonney has described an instructive case of conversion of greenstone into schist on a small scale in the Bernina region, Q.J.G.S., 1894, p. 279 et seq.

² This idea was suggested for contained boulders by Professor Charles Lapworth in connexion with the Carboniferous conglomerates of Halesowen in Worcestershire.

³ *Traité de Géologie*, 5th ed., vol. iii, p. 1492, 1906.

⁴ Q.J.G.S., vol. lviii, p. 620 (Sand of Bunter Pebble-bed), 1902; vol. lxx, p. 229 (New Red Sandstone), 1909.

⁵ Proc. Geol. Assoc., vol. xxiv, p. 57, 1913.

⁶ Trans. Geol. Soc. Glasgow, vol. xiv, p. 271, 1912.

source of the Pliocene material was from the area of the Ardennes, etc., on the south-east, but that the minerals of the Eocene beds were derived from an entirely different direction, possibly from the west or south-west. The overlying Lower Glacial deposits were derived, as their boulders also indicate, from the north, and possibly the north-east and north-west. These are broad generalizations only, but the subject is susceptible to more exact treatment which would lead to a correspondingly closer realization of ancient changes in geography.

Unconformities are usually emphasized by the changes in mineral composition, and these support palæontological and field-evidence. Changes in the distribution of land and water and in the direction of the large rivers are thus revealed. As an outstanding example may be mentioned the contrast between the fine-grained residues, consisting largely of staurolite, kyanite, tourmaline, hornblende, and pyroxene, which are characteristic of the London Clay in Suffolk, and the coarse muscovite, red garnet, andalusite, staurolite, epidote, etc., of the overlying Boxstones at the base of the Crag of Rupelian, Miocene, or Diestian age.

Recent work has possibly had a tendency to lead geologists to expect too much in certain directions from the comparative study of the residues of sediments, and it should therefore be stated at once that it is improbable that mineral constitution will have any correlative value over wide areas, certainly not comparable with that of fossils. From the nature of the subject we should expect various portions of basins of deposition to derive their material from different directions and sources. The writer has, however, endeavoured to show recently that mineral constitution, when fossils are rare or lacking (and if present, of wide range), has a distinct stratigraphical value over limited areas, when abundant samples are collected from numerous localities and horizons.¹ For this purpose the mineral assemblages of all the divisions of each of the geological stages of a district must be known. In connexion with these statements it should be said that the mineral assemblage of the Lower Greensand over most of its outcrop very closely resembles that of the Reading Beds of South-East Suffolk and Northern Essex, which beds in turn are extremely similar in mineral composition to the Bagshot Beds of the area around Claygate and Oxshott in Surrey. Again, the mineral constitution of the various divisions of the Eocene beds in East and West Kent is much more similar throughout than in the corresponding divisions in East Anglia, where there is a greater variety of minerals. The respective Thanet Beds, Woolwich and Reading Beds, etc., in the two areas do not resemble each other in petrology, and no correlation could be attempted on such evidence alone. The composition of the Thanet Beds around Lille, as detailed by L. Cayeux,² is again different from either.

Nevertheless, there are broad groupings which hold over a considerable area. Although the members of the Eocene Series differ among themselves, and each member may vary in composition over

¹ *Abstr. Proc. Geol. Soc.*, No. 973, p. 76, etc., 1915.

² *Ann. Soc. Géol. Nord*, vol. xix, p. 264, 1891; also p. 90.

a wide area, all the Eocene beds in the London Basin appear to conform more or less to a general type characterized by the occurrence of abundant kyanite, staurolite, tourmaline, zircon, and rutile, and less commonly, green hornblende and small colourless garnets. The various beds of the Pliocene Series from Cornwall to East Anglia and Belgium all possess more or less similar mineral assemblages, the chief members of which are red garnet, muscovite, andalusite, staurolite, epidote, etc. The distinction from the Eocene Series is very marked.

As a final example may be quoted the sands forming the lowest part of the Inferior Oolite, the mineral composition of which is very distinctive, and yet maintains practically the same character when the beds are traced from Yorkshire by way of Northampton, the Cotteswolds, Bath, and Yeovil to the Dorset coast.

While correlation of smaller geological divisions over considerable areas is fraught with difficulty, the mineral constitution of the different beds is of great stratigraphical value, as has been stated, over limited areas. It has been shown, for example, that the Thanet Beds, Reading Beds, and London Clay in East Anglia have each a characteristic mineral assemblage by which they may be recognized, provided that we know also the mineral composition of all the other Tertiary beds from the top of the Chalk to the post-Glacial and Recent.¹ Speaking generally, each mineral assemblage remains constant over an area of nearly 500 square miles, and appears to be independent of the lithological variations of the bed containing it.² That there is a limit to this constancy is shown by the fact that the Reading Beds, when traced as far to the south-west as Bishop's Stortford and Hertford, begin to show a variation in mineral character. The change in mineral composition of the Reading Beds with respect to the underlying Thanet Beds may be due in part to difference of mechanical composition, and therefore to difference in conditions of deposition, resulting in concentration of certain minerals and decomposition of others, but whatever may be the cause the variation observed has an important stratigraphical value. The green and brown hornblende, pyroxene, biotite, apatite, etc., of the Thanet Beds disappear, and it is not until we reach the London Clay that some of these minerals reappear. The large and characteristic grains of kyanite, staurolite, and tourmaline present in the Reading Beds have disappeared in the London Clay, but green hornblende becomes abundant, and muscovite and colourless garnets more common. The detrital material is of fine grain, and therefore provides the more contrast with the very coarse stuff found in the Boxstone Bed at the base of the Suffolk Crags.

¹ Abstr. Proc. Geol. Soc., No. 973, p. 76, 1915.

² Very recently (March, 1916), in a lecture before the Geologists' Association, my friend and colleague, Mr. V. C. Illing, has claimed that the horizons of the unfossiliferous and oil-bearing sediments of the south-western part of Trinidad may be identified and correlated over a limited area by means of their mineral assemblages. If this contention is supported by the evidence (and from an examination of the residues I believe it is), the hitherto purely academic study of the petrology of sediments becomes at one bound of great economic importance.

The composition of the different zones of the Coralline, Red, and Norwich Crag is similar to, but not of so rich a type as, that of the Boxstones. The Chillesford Beds (late Pliocene) are much enriched in muscovite. The Westleton Beds (? early Pleistocene) show, as compared with the Pliocene beds below and the glacial deposits above, rather an impoverished assemblage which may have been derived from the Chalk and Eocene beds with a slight admixture of Crag detritus (garnets, etc.). The purity of the Westleton pebble-beds (mainly flint and quartz) and freedom from foreign boulders is interesting in this connexion. The glacial deposits yield, as no doubt would be expected when the variety and extent of the rocks laid under contribution are considered, a very rich mineral suite, the abundance and variety of which are unparalleled by any other deposit, and only approached by the Pliocene. Abundant garnets, amphiboles, and pyroxenes (sodic varieties included), epidote, micas, apatite, staurolite, kyanite, tourmaline, etc., make the deposits easily recognizable under the microscope or high-power hand-lens ($\times 20$). It is noteworthy that andalusite is not nearly so abundant as in the Crag or in the glacial deposits of the West of England. The post-glacial gravels, sands, and brickearths, and the river terrace sands, loams, and alluvium, contain similar mineral assemblages to the glacial beds, and are no doubt derived largely from them.

The value and limitations of the application of petrographic methods to stratigraphy are well illustrated by the consideration of a sequence of deposits in one area such as that just mentioned.

First we may consider the limitations (apart from those resulting from attempted wide correlation). The Upper and Lower Glacial beds of East Anglia differ much in field characters, in mechanical composition, and in their included boulders, indicating two different directions of advance for the ice which produced them. It is very difficult, however, to tell the Upper from the Lower beds by the heavy detrital mineral assemblage, notwithstanding the fact that their mechanical analyses conform to two very different types. This may be due to the mineral richness of each. Again, it was hoped that the various zones of the Red Crag, when traced northwards, might show, together with the increasingly boreal fauna, a corresponding change in mineral constitution (the basin was closed on the south and opened on the north in late Pliocene times). No such variation has been observed, and it seems probable that the drainage direction and rocks undergoing denudation to produce the Crag sands, etc., remained the same throughout Pliocene times.

On the other hand, the advantages of the method are great. It has now become possible to identify any East Anglian bed (allowing for the limitations just detailed) from its detrital mineral suite, and to say when the mineral assemblage of any particular bed is pure, or when it has been contaminated with an admixture of material from another bed. A few actual examples may be quoted. Considerable glacial disturbance of the East Anglian deposits has frequently taken place locally in Southern Suffolk, etc., and it is often desirable to know whether a limited exposure shows a bed *in situ*, undisturbed and uncontaminated. Should the bed have been redeposited in

Glacial times, even if its original characters are retained, its detrital minerals tell their tale. The pale sands of the Reading Beds, Crag, and Glacial beds often resemble one another closely, and it has hitherto been difficult or impossible to identify with certainty an included mass of such sands in a large glacial disturbance.¹ Examination of the mineral assemblage allows a determination to be made, for example, as to whether the sand is a pure Reading Sand or one contaminated by an admixture of glacial detritus.

The pebble-bed at the base of the London Clay (on the horizon of the Blackheath Beds of the South of England) has in places in East Anglia been rearranged upon the shores of the Crag sea. This is indicated at times by the iridescent ferruginous coating upon the pebbles and the admixture of teeth and coprolites in the bed, but in some cases, except for the presence of reddish sand, it is difficult to say whether the bed is of Eocene or Crag age (that is, rearranged in Red Crag times). An analysis of the sandy material of the bed is sufficient to settle the point, for the Pliocene minerals are distinctive and easily recognizable, while those of the normal Eocene pebble-bed conform to the suite of the Reading Beds.

In the area where overlap of the Thanet Beds by the Reading Beds takes place (in South-West Suffolk and North-West Essex), the latter assume the lithological characters of the former and rest directly on the Chalk. They contain a 'bull-head' flint-bed, and are glauconitic clayey sands. When isolated sections in Drift-covered outliers occur on the north-west of the main outcrop, it is sometimes a matter of difficulty, as, for example, at Kedington in the Stour Valley, to refer the bed observed to its proper place in the geological sequence. The detrital minerals of the sands will usually be of service, and in the case quoted it was found that, while the Kedington deposit had the lithological characters, etc., of the Thanet Beds, its mineral composition showed it to be an outlier of Reading Beds, resting on the Chalk, but one which had been rearranged on the shore of the Crag sea. Cases might be multiplied, but the limited utility of the method must be apparent.

At present it is premature to discuss the question of the stability of minerals in geological time. The controversy upon the extent to which andalusite occurs in pre-Pliocene sediments in Western Europe is still fresh in our minds. The allied mineral, kyanite, appears to have a well-marked earlier limit in the English area, but how far the presence or absence is due to drainage direction is not certain. The extraordinary abundance of sharply crystalline apatite at a loamy horizon of the Thanet Beds near Ipswich, protected by a cover of Chalky Boulder-clay, is noteworthy as showing how an easily decomposable mineral may be preserved.

The investigation of sediments 'hermetically sealed' shortly after their formation, as, for example, gypsiferous deposits in the Permian and Trias, may by comparison yield interesting information as to the amount of decomposition which takes place in heavy minerals subsequently to their deposition.

¹ The disturbance referred to may be 150 yards long and 40 feet deep.

Oscillatory and alternating current action has an effect, not only in eliminating the more easily decomposable minerals (e.g. some of the ferromagnesian minerals, apatite, andalusite, etc.), but also in concentrating the heavy detritus by a kind of natural jiggling or panning. 'Pay-streaks' may thus be produced. Parts of the pebbled under the London Clay in Suffolk exhibit an enrichment in zircon, rutile, ilmenite, and magnetite by this action, especially when there is evidence of current-action and contemporaneous erosion.

The lenticles of grains of titaniferous hæmatite occurring in the basal Cambrian conglomerates of St. Non's Bay, near St. David's,¹ may have a similar origin. The richness of the Bagshot Beds in the heaviest minerals may be attributed to a like cause.

As opposed to this concentration, we have the elimination of minerals (other than those which are more or less unstable) by conditions of deposit. The work of Thoulet and Retgers has shown that micas are absent from certain wind-formed deposits such as desert and dune sands, but examination of British blown-sand dunes has revealed their presence. Topaz tends to form flakes on account of its good basal cleavage, and may well float away; it has been suggested that andalusite may be lost in this way, by floating off during natural or artificial panning. The scarcity of apatite in many deposits is probably due to its disappearance by solution. It is more abundant in clays and loams than in sandstones where percolation is easy, but it does also occur in the latter. When the sediment has to be cleaned by long boiling with acid, much apatite undoubtedly dissolves, but, as in the case of the Boxstone Bed, some still remains. Professor C. G. Cullis and Professor W. G. Fearnside have both suggested that the difference in solubility may be due to the presence of either or both chlor- or fluor-apatite, but usually the grains are so small, and the occurrence so uncommon, that micro-chemical proof is difficult.

What may be called the intensive study of an area of sedimentary rocks of various geological ages, surrounding an igneous or metamorphic complex, is at present very necessary for the advancement of our work on the petrology of sediments. For this purpose we need to know exactly and in detail the mineral composition of neighbouring crystalline rocks, slicing alone not being sufficient. Crushing must be resorted to, and panning and separation with heavy liquids, in order that we may be certain of knowing all the accessory and rarer minerals and their relative abundance.² Following this, the study of the neighbouring sediments of varying geological age, considered stratigraphically, cannot fail to yield valuable data which will serve to indicate the extent to which the differences observed in assemblages of detrital minerals may be caused by direction of drainage, conditions of deposition, stability of minerals in geological time, and contemporaneous or subsequent sealing of minerals in sedimentary rocks.

¹ W. Jones, *Proc. Geol. Assoc.*, vol. xxii, p. 232, 1911.

² R. H. Rastall & W. H. Wilcockson, *Proc. Geol. Soc.*, p. lxxx, 1915.

IV. CONCLUSION.

Detrital mineral assemblages are of considerable value for stratigraphical purposes over limited areas, but except for very broad divisions, as e.g. Eocene and Pliocene beds, cannot be used for wide correlations. Unlike fossils, minerals cannot show an evolutionary sequence or gradual variation, and there being comparatively so few species occurring in detrital sediments the number of combinations is very limited. Mineral suites, unlike life assemblages, therefore tend to recur. As in the case of minerals of igneous rocks, the relative abundance of the heavy components in sediments is of great determinative value. Mere lists of detrital minerals occurring in sediments are therefore not sufficient; we need to know the size, colour, form, degree of alteration (if any), and other characters of each mineral, as well as its relative abundance.

The zonal value of mechanical and mineral analyses has not yet been determined, partly because the rocks which yield the best heavy mineral crops, such as sandstones, loams, etc., do not lend themselves to zoning by fossils, while the clays and limestones, which often contain valuable life assemblages, contain frequently only a very small quantity of heavy minerals (other than authigenic). The connexion between the mechanical composition (e.g. of clays), as indicating differences in condition of deposit, and the contained faunas of various zones, has yet to be worked out, but the results may well be interesting.

The goal to be aimed at is a knowledge of the mineral and mechanical composition of every sedimentary rock in the British geological column, collection of material being made over as wide an area as possible. Cores of borings, as well as the records only, must be carefully preserved, and the beds met with subjected to similar analyses. The information obtained should be correlated with that yielded by the distribution of isopachytes and sub-surface contours.

V.—SEDGWICK MUSEUM NOTES.

NOTES ON THE GENUS *TRINUCLEUS*. Part IV.

By F. R. COWPER REED, M.A., Sc.D., F.G.S.

(Concluded from the March Number, p. 123.)

MORPHOLOGICAL CORRELATIONS.

WE have now finished the survey of the characters of the head-shield of *Trinucleus* sufficiently to enable us to discuss the vexed questions of the affinities, systematic position, and evolution of the genus; and from the foregoing details of the various species we can perceive that there are many difficult problems presented when we attempt to correlate its structure with that of other trilobites. Whether the peculiar characters of the genus are the result of degeneration or of the persistent retention of early phylogenetic stages or of a reversion to such stages is a matter of dispute.