15. *A* CONTRIBUTION *to the* PETROGRAPHY *of the* NEW RED SANDSTONE *in the* WEST *of* ENGLAND. By HERBERT HENRY THOMAS, M.A., B.Sc., F.G.S. (Read March 10th, 1909.)

[PLATE XII.]

CONTENTS.

I. INTRODUCTION.

IN a former paper [1] communicated to this Society I dealt with the mineralogical constitution of the great Pebble-Bed, as developed in Devon and Somerset. The results obtained encouraged me to undertake a similar study of the other members of the New Red Sandstone Series in that district; and, in the following communication, I have endeavoured to point out the mineralogical and physical differences exhibited by the microscopic particles which form the finer portions of the deposits. The classification and subdivision of the New Red Sandstone Series in Devon and Somerset has gradually evolved from the labours of several geologists, and I propose to use those subdivisions which are now adopted by the Geological Survey.[2]

The New Red Sandstone in the area under consideration may be divided as follows, commencing with the older beds:—

(1) Lower Breccias and Lower Sandstones.
(2) Lower Marls.
(3) Pebble-Bed and Conglomerate.
(4) Upper Sandstones and Marls, with the Upper Keuper Sandstones of the Bridgwater district.

These subdivisions are founded solely on lithological characters, and therefore form the most natural basis for a petrographical study.

The Lower Breccias are well-developed, and have been examined on the south coast at Teignmouth and Dawlish, along the western side of the Exe estuary on the flanks of the Haldon Hills, in the Exeter district, and in the Crediton and Stogumber valleys. They usually consist of deep-red breccias, sands, and sandstones, most

[1] 'Mineralogical Constitution of the Finer Material of the Bunter Pebble-Bed in the West of England' Quart. Journ. Geol. Soc. vol. lviii (1902) p. 620.

[2] W. A. E. Ussher, 'Geology of the Country around Exeter' Mem. Geol. Surv. 1902; see also 'Subdivisions of the Triassic Rocks, between the Coast of West Somerset & the South Coast of Devon' Geol. Mag. dec. 2, vol. ii (1875) p. 163.

often loose and incoherent, but occasionally compacted into rocks of more solid character.

The Lower Sandstones, which for the most part occupy a position above the breccias, have been studied on each side of the Exe estuary, in the vale of the Clyst, in the neighbourhood of Killerton and Brampford Speke, and in the Bridgwater area. They present many points of similarity to the sands and sandstones interbedded with the lower breccias.

The Lower Marls, consisting of red marls with sandstone-courses, the Pebble-Bed, and the Upper Marls and Sandstones have been dealt with from numerous localities in the two counties.

At first I confined my attention to that part of the country which lies between Wiveliscombe on the north, and the south coast of Devon; but later, at the instigation of Mr. Ussher, I extended the work so as to include the red rocks lying to the west and east of the Quantock inlier, in the districts of Taunton and Bridgwater.[1]

Nearly one hundred samples were collected from various localities and horizons, each sample receiving the following treatment:—The sand or crushed sandstone was first put through a fairly fine sieve, so as to separate out the larger rock-fragments and leave, as far as possible, simple mineral grains. The coating of iron-oxides was then removed from the grains forming the finer portion, which, after washing and drying, was subjected to two fractional separations by means of Thoulet's solution.[2] Three residues were thus prepared from each sample, of which portions were mounted for microscopical study. One residue contained all those minerals present in the sample which had a specific gravity greater than 2·8, the other two respectively contained the bulk of the quartzose and of the felspathic material. The heaviest residue is in general a very small percentage of the whole sample, but at the same time the ratio of the lightest part to the heavier varies considerably in all divisions of the New Red Sandstone.

In some respects, the treatment of sands and sandstones with hydrochloric acid is disadvantageous: for, while the iron-oxide, which coats the grains, is removed, it is probable that some of the less stable minerals are attacked and even eliminated. If, however, after such treatment mineralogical differences can be detected in the residues from various samples, such distinctions are obviously the most reliable: for, if our considerations extended to minerals easily attacked by acids, we should then deal with minerals which might be removed locally from the deposit by natural chemical agencies, and this would give misleading ideas as to their distribution.

[1] 'Geology of the Quantock Hills, &c.' Mem. Geol. Surv. 1908, pp. 60–64.

[2] A solution of the double iodide of mercury and potassium in water. Although it has a great drawback in its poisonous nature, I have found it by far the cleanest to handle and the easiest of recovery. It has many advantages over other heavy liquids; it is less viscous than a solution of cadmium-borotungstate of the same density, and is not so prone to develop convection-currents with slight changes of temperature as in the case of the more mobile organic fluids (bromoform, etc.).

II. The Minerals of the New Red Sandstone.

The following is a list of the constituents, hitherto identified, forming the finer material of the New Red Sandstone; the minerals are arranged according to their crystallographic systems:—

(i) *Cubic.*
- Fluorspar.
- Garnet.
- Magnetite.

(ii) *Tetragonal.*
- Anatase.
- Cassiterite (?).
- Rutile.
- Zircon.

(iii) *Rhombohedral.*
- Apatite.
- Calcite.
- Ilmenite.
- Hæmatite.
- Quartz.
- Tourmaline.

(iv) *Orthorhombic.*
- Barytes.
- Brookite.
- Celestine.
- Cordierite (?).
- Sillimanite.
- Staurolite.
- Topaz.

(v) *Monoclinic.*
- Actinolite.
- Biotite.
- Chlorite.
- Muscovite.
- Orthoclase.
- Sphene.

(vi) *Triclinic.*
- Cyanite.
- Microcline.
- Plagioclase-felspars.

In addition to the simple mineral-grains, compound grains and mineral-aggregates are common, including leucoxene, perthitic intergrowths of felspar, serpentine, and micaceous decomposition-products (presumably after some aluminous silicate, such as cordierite, andalusite, or cyanite); grains of chert, felsite, micropegmatite, and mica-schist are of frequent occurrence.

Among the minerals acting as cements may be mentioned calcite, limonite, hæmatite, barytes, celestine, and gypsum.

It will be seen, on comparing the foregoing list with that given in my previous paper, that the mineral species present in the New Red Sandstone as a whole are, with a few exceptions, those already noted from the Pebble-Bed. In the following description of certain mineral species it is intended only to supplement the descriptions already given.

Those minerals which are now mentioned as occurring in New Red sediments for the first time, or appear to call for treatment in somewhat greater detail, are—anatase, calcite, hæmatite, quartz, tourmaline, barytes and celestine, cordierite (?), staurolite, topaz, actinolite, chlorite, and selenite.

Anatase.—This mineral occurs in two distinct habits: (*a*) tabular and (*b*) pyramidal.

(*a*) The tabular variety consists usually of colourless or sometimes pale-yellow crystals, rarely exceeding 0·1 mm. in greatest width. The basal plane (001) is large, and the pyramid-planes {111} exceedingly narrow. The crystals are either single and well formed, or are seen to consist of several crystals in parallel intergrowth as figured by Thürach,[1] Cayeux,[2] and others (Pl. XII, fig. 1, *a* & *c*). Occasionally, the basal plane is absent, and its place is taken by low pyramids of some form such as {h h l}, as in the specimen from the Lower Breccias of the Ness at Teignmouth (Pl. XII, fig. 1 *b*).

(*b*) The pyramidal variety occurs in steel-blue or yellow crystals with the basal plane small or absent, and having well-developed pyramid-planes modified only by narrow prisms {110}. The pyramid-planes are deeply striated parallel to their intersection with the prism (Pl. XII, figs. 3 & 5). These forms are accurately described by Thürach, who, in addition, mentions microscopic anatase with a pyramid of the second order {h o l} and a double pyramid {h k l}. These I have not noticed on any crystals from the New Red rocks.

Anatase belongs essentially to the crystalline metamorphic rocks; but it may be formed from a variety of titaniferous minerals on their decomposition, as, for instance, from ilmenite, sphene, etc.[3] Mr. J. B. Scrivenor described the alteration of ilmenite into anatase (Pl. XII, fig. 7) in the Triassic sandstones of Cheshire,[4] and stated that in his opinion the change had taken place since the deposition of the sandstone. In the south-western area I have observed many crystals of anatase attached to ilmenite or leucoxene; and there is little doubt, from the sharpness of the angles and the general fragility of the crystal-groups, that nearly all the tabular anatase has been formed as Mr. Scrivenor suggested.

Some of the pyramidal and more acute forms, however, show unmistakable signs of wear; their edges are rounded, and the crystals themselves far from perfect. These most certainly have been derived from pre-existing rocks.

Calcite.—Calcite enters into the composition of most of the New Red rocks in the neighbourhood of calcareous inliers of older rocks, and in some divisions of the Red rocks far removed from such calcareous masses. It occurs chiefly as a calcareous cement, but most probably also as detritus. Some of the upper marls are remarkable for their high percentages of calcium-carbonate when quite remote from any older calcareous rocks.

Hæmatite.—This mineral also occurs as a cement, and is often associated with secondary growths of quartz. It exists as thin plates coloured a deep red; also as minute botryoidal grains, made up of spheroidal masses with radiate structure which give a black cross between crossed nicols. It is evidently of secondary origin.

[1] 'Ueber das Vorkommen mikroskopischer Zirkone & Titan-Mineralien in den Gesteinen' Würzburg, 1884.

[2] Mém. Soc. Géol. du Nord, vol. iv, no. 2 (1897) pl. x.

[3] A. Lacroix, 'Sur qq. Cas de Production d'Anatase par Voie Secondaire' Bull. Soc. Franç. Min. vol. xxiv (1901) p. 425. See also W. Prinz, 'Les Oxydes de Titane .... de qq. Roches du Brabant' Bull. Soc. belge Géol. vol. xxi (1907) Mém. p. 383.

[4] Min. Mag. vol. xiii (1903) p. 348.

Quartz.—Quartz, which generally forms more than 50 per cent. of the New Red sands, may, for purposes of description, be divided into primary and secondary.

The detrital or primary quartz may be further divided, according to whether it gives a uniform or an undulose extinction; and, following Dr. W. Mackie,[1] may be subdivided according to the nature of its inclusions, the inclusions being the best guide to the character of the rock from which the quartz was derived.

The subdivisions of the detrital quartz are as follows:—

(a) Quartz with included minerals presenting a regular outline, such as apatite, stumpy crystals of tourmaline, etc.

(b) With acicular inclusions, such as hair-like rutile, fibrous sillimanite, and needles of blue tourmaline.

(c) With irregular inclusions, such as patches of brown glass, small masses of felsitic matter, fluid, and gas.

Secondary quartz is not of common occurrence in the New Red sands of the West of England. It was stated by the Rev. A. Irving[2] that the angularity of the grains forming the sands and sandstones of the great Pebble-Bed seemed to be largely due to the deposition of secondary quartz; but, although a thin coating of this material is occasionally met with, it cannot in any sense be regarded as a general feature. It rarely acts as a cement, but tends to produce doubly terminated pyramidal crystals with a quartz-grain as a nucleus.

Tourmaline.—This mineral is present in the heavy residues from sedimentary rocks of all ages, but in the New Red rocks it occurs in three distinct varieties. The most common variety is, generally speaking, of a deep-brown colour, and exists either as short stumpy prisms terminated by the simple rhombohedron, or as rounded to spherical grains.

A light-blue variety occurs plentifully in some of these rocks, occasionally in greater abundance than the deeper coloured type mentioned above. It is nearly always acicular, and slender crystals are often grouped together in roughly radiating bundles. The needles show little or no sign of terminal planes, and the groups occur either free, or embedded in quartz after the manner of luxullianite. The point to which the individual rays of a group converge is often of a brown colour.

The third variety is evidently connected chemically with the above-mentioned blue acicular crystals, but differs in its habit. It occurs as pale to deep blue, thin hexagonal plates (Pl. XII, fig. 6) flattened parallel to the base {111}. The rhombohedra are represented by narrow planes truncating the horizontal edges. The crystals occasionally show a zonal structure in various shades of blue, and always the emergence of an optic axis.

The basal plane {111} is one not usually met with on tourmaline-crystals, and it seems unlikely that it would be so largely developed

[1] 'Sands & Sandstones of Eastern Moray' Trans. Geol. Soc. Edin. vol. vii (1893–99) pp. 148–72; see also H. C. Sorby, Quart. Journ. Geol. Soc. vol. xxxvi (1880) Proc. p. 46, and Monthly Microscop. Journ. vol. xviii (1877) p. 209; also J. A. Phillips, Quart. Journ. Geol. Soc. vol. xxxvii (1881) p. 6.

[2] Quart. Journ. Geol. Soc. vol. xlviii (1892) p. 71.

as to form crystals of this shape. It is probable, therefore, that in these crystals the true basal plane is not present, but that some external factor has determined a tabular habit. In all probability, these crystals were formed between the cleavage-planes of mica, and thus had their dimensions restricted in the direction of the vertical axis.

It appears that flaky crystals giving an interference-figure were detected by Mr. T. H. Cope[1] in the titaniferous iron-sands of Porth-Dinlleyn, on the coast of Carnarvonshire.

Barytes and celestine.—Both these minerals, more especially barytes, are met with as cementing materials, but (so far as can be judged) never as detritus. Many of the sandstones and marls, when broken up and separated by heavy solutions, give a large residue. The barytes under the microscope consists, as might be expected, of small rectangular grains bounded by the two good cleavages $\{001\}$ and $\{110\}$. It is associated with celestine, but the two minerals are indistinguishable in microscopic grains. They are easily identified, however, by their respective flame-tests; and, when occurring together, the presence of both is easily demonstrated by spectroscopic methods.

Celestine has been recorded from the Upper Marls of Peake and Salcombe Hills, near Sidmouth, by Mr. S. G. Perceval.

Cordierite (?).—Only one grain which might possibly be referred to unaltered cordierite has been met with, and that from the Lower Sandstone of East Town, east of Totland, in the Quantock region. It occurred as a somewhat rounded grain, with traces of a moderately good cleavage. It gave straight extinction, and showed feeble pleochroism from pale blue-grey to an indistinct shade of yellow. It contained a large number of minute opaque inclusions, probably iron-ores. No pleochroic halos were noticed. If this mineral is really cordierite, its occurrence is most unexpected; for, in rocks of this character, it would probably occur altered to pinite, or some other decomposition-product.

Staurolite.—On some horizons this mineral forms quite a considerable portion of the heavy residues, and is one of the most abundant heavy minerals. It occurs most often, in these rocks, in angular and rough grains of a pale-yellow to amber colour, measuring up to 0·5 mm. in greatest length. The angularity (Pl. XII, fig. 4 *c*) is due to the fraying-out of the mineral along the prism-cleavages parallel to the form $\{110\}$. The cleavage parallel to the form $\{010\}$ is also a prominent boundary-plane.

Very rarely it occurs in well-formed crystals. In the New Red rocks such good crystals as those figured in Pl. XII (figs. 4 *a* & 4 *b*) have not been met with. For descriptive purposes, therefore, I have shown two almost perfect crystals from more recent sediments, one from the Pliocene of Lenham, and the other from the blown sand of Newgale in Pembrokeshire. These crystals are tabular parallel to

[1] Proc. Liverp. Geol. Soc. vol. ix, pt. ii (1901–1902) p. 212.

the cleavage {010}. The long edges are modified by the prisms {110}, and the crystals are terminated by the forms {101} and {001}. The large flat face (010) is normal to the obtuse bisectrix ($\mathfrak{a}$), and the axis of elongation ($=\mathfrak{c}$) lies in the plane of the optic axes. The pleochroic scheme for these crystals is

$\mathfrak{a}$ = pale straw-yellow; $\mathfrak{b}$ = deep yellow.

Angular grains similar to those usually occurring in the Red rocks have been noted by many authors from a variety of sediments, including Cayeux from the Chalk, René Bréon from the marine and dune-sands of Britanny, Retgers from the dune-sands of Holland, Thürach from the sands of the Sahara, and Artini [1] from the alluvium of the North Italian rivers.

Topaz.—Topaz occurs sparingly as angular cleavage-fragments in the Lower Breccias and at some localities in the Pebble-Bed. The flakes are colourless, and give an interference-figure in convergent light showing an angle between the optic axes, in air, of about 110°. Usually, they are only thick enough to show the colours of the first order, and are full of gaseous and fluid inclusions.

Actinolite.—This mineral has been met with as pale-green acicular and fibrous aggregates, usually associated with pink garnet. The pleochroism is distinct, the greater absorption occurring in a plane at right angles to the axis of elongation of the needles. It presents the usual characters of actinolite from metamorphic rocks, and is the only amphibole that is known to occur in the Red rocks of this district.

III. Physical Characteristics of the Finer Material.

The grains forming the matrix of the Lower Breccias are invariably angular or but slightly rounded, thus presenting features almost identical with those of the larger rock-fragments with which they are associated. In the intercalated beds of sand and sandstone, however, a great difference in the grain is apparent. The particles forming these finer deposits are always well worn, and usually more so than those of the ordinary marine sands or dune-sands of coastal regions. In fact, many samples approximate very closely to the 'millet-seed' sands of deserts. This feature in connexion with British red sandstones has been pointed out by Phillips, Goodchild, and others. Sands of this type occur at Berry Head,[2] the western

[1] Riv. di Min. & Crist. Ital. vol. xix (1898) p. 33. Speaking (*ibid.* p. 41) of the staurolite from the River Adige, he says that it is 'Piuttosto abbondante, quasi sempre in granuli irregolari, a spigoli vivi; scarse inclusioni, colore vivace, pleocroismo distinto.'

[2] The rock at Berry Head occupies a fissure in the older rocks, and forms a pipe or dyke of fairly compact sandstone. The cementing-material is partly ferruginous and partly siliceous. Similar dykes have been noted in other districts (W. Pengelly, Trans. Devon. Assoc. vol. i, 1864, p. 40; also E. B. Tawney, Proc. Bristol Nat. Soc. n. s. vol. i, pt. ii, 1875, p. 162). In my former paper in this Journal I erroneously regarded the Berry Head rock as a possible outlier of Pebble-Bed; but, as pointed out by Pengelly and impressed upon me by Mr. Ussher, it must belong to an earlier, if not the earliest, period of the New Red Sandstone.

extremity of Torbay, and associated with the breccias of Dawlish and Heavitree (near Exeter).

The cementing-material in the Lower Breccias is almost always of a ferruginous nature, only becoming calcareous in the neighbourhood of limestone-masses of Devonian or Carboniferous age. A complete silica-cement never occurs; but secondary growths of silica have been noted in a few cases (as, for instance, Berry Head). Lithologically, the Lower Sandstones are similar to the beds of sand and sandstone associated with the Lower Breccias, and the same remark applies to the cementing materials.

The particles are all well rounded; but the rounding is most complete in the centre and south of Devon, especially in the Broad-Clyst district. Around the Somerset inliers of older rocks the rounding is not so well marked.

The grains forming the marls below the Pebble-Bed, owing to their extremely small dimensions, cannot readily be compared with those of other New Red divisions. The material, as might be expected from the size of the particles, is all angular; but, when it becomes sufficiently coarse to form beds of sand or sandstone, the grains are rounded. Well-rounded sands occurring in the Lower Marl subdivision have been noticed at St. Mary's Clyst, Hulham (near Exmouth), and several other localities; but the rounding is never so complete as in the sands of the lower divisions, and approximates more to that observable in the grains forming the matrix of the Pebble-Bed.

The finer grains of the Pebble-Bed are remarkably constant in character: they are subrounded, after the manner of fluviatile or marine sands. The constituents of the matrix of the Upper Marls and Sandstones, and of the Upper Keuper Sandstones of the Bridgwater area, are all angular to subrounded, according to size. Generally speaking, the rounding of the grains is less marked in this division of the New Red than in the sands of any other division.

With regard to the cementing-materials in the Upper Marls and Sandstones, in addition to the usual ferruginous material we find that calcium-carbonate is almost universal, and that substances such as barytes and gypsum play an important part locally.

In the marls, often far removed from any limestone-outcrop, the percentage of carbonate is extremely high: for instance, four samples taken from the deep boring at Lyme Regis[1] yielded the following percentages of carbonate, estimated as $CaCO_3$:—

Depth of 487 feet................. ...	11·51
,, 850 ,, ...	16·49
,, 1200 ,, ...	21·10
,, 1300 ,, ...	12·26

Barytes was a prevalent constituent of a sample taken from a depth of 1000 feet, and undoubtedly existed as a cement.

[1] A. J. Jukes-Browne, Quart. Journ. Geol. Soc. vol. lviii (1902) p. 284.

In the case of the calcium-carbonate of these rocks, much of it presumably resulted from chemical precipitation; but, at the same time, it appears that a fair proportion must have been detrital in character.

IV. Mineralogical Characteristics of the Finer Material and Distribution of Mineral Species.

The following is a list of localities from which samples have been collected for petrological study:—

Lower Breccias and Lower Sandstones.

1. Berry Head, south of Brixham. Sandstone.
2. Torre. Sandstone.
3. The Ness, west of Teignmouth. Breccia.
4. The Clerk Rock, east of Teignmouth. Breccia.
5. Heavitree, near Exeter. Breccia and sandstone.
6. Yeoford Junction, north of. Breccia.
7. Hollis Head, near Killerton. Breccia and sandstone.
8. East of Langley, north of Wiveliscombe. Breccia.
9. Topsham (Redcow). Sandstone.
10. Topsham (railway-bridge). Sandstone.
11. Sandygate. Sandstone.
12. Honiton Clyst. Sandstone.
13. Monkerton, near Pinhoe. Sandstone.
14. Gipsy Hill, near Pinhoe. Sand.
15. Broad Clyst Heath. Sand.
16. Digby's Asylum. Sandstone.
17. Brampford Speke. Sandstone.
18. East Town, east of Totland. Sand.
19. Wiveliscombe, south of Castle Hill. Marly sandstone.
20. Stogumber. Sand.
21. Elworthy, outlier near. Sand.

Lower Marls.

22. St. Mary's Clyst. Sandstone.
23. Hulham, near Exmouth. Sandstone.
24. Raddon Quarry, near Thoverton. Marl.
25. Uffculm, south of. Marl and sandstone.
26. Wiveliscombe, east of. Sandstone.

Pebble-Bed.

27. Budleigh Salterton, coast-section, samples taken every 10 feet from base to summit. Sand.
28. Woodbury Castle, 20 feet above the base. Sand.
29. Newton Poppleford. Sand.
30. Fair Mile, near Talaton. Sand.
31. Uffculm, south of. Sand.
32. Burlescombe, Church Quarry. Sand.
33. Milverton Station, quarry at. Calcareous sandstone.
34. Fitzhead, east of Wiveliscombe. Calcareous sandstone.

Upper Sandstones and Marls.

35. Ladram Bay, east of Budleigh Salterton, coast-section. Sandstone.
36. Lyme Regis, deep boring at, depth of 487 feet. Marl.
37. Lyme Regis, deep boring at, depth of 1000 feet. Marl.
38. Lyme Regis, deep boring at, depth of 1200 feet. Marl.
39. Otterton. Marly sandstone.
40. Crowcombe, west of. Sandstone.
41. Bishop's Lydeard, quarry near. Sandstone.
42. North Petherton, Bridgwater area. Sand.
43. Chads Hill, south side of Cannington inlier. Sandstone.
44. Plainsfield, east of, east of the Quantocks. Sand.
45. Cannington Park Farm. Sand.
46. Nynehead, road and quarry near. Sandstone.
47. Wembdon, near Bridgwater. Sandstone.
48. Preston Bowyer. Sandstone.

Upper Keuper Sandstone.

49. Stoke St. Gregory. Sandstone.

The following table (pp. 238–39), in which the numbers refer to the localities mentioned above, presents the distribution of the more important and abundant minerals, exclusive of quartz, which enter into the composition of the New Red sediments.

Table I.—*Distribution of mineral*

[+ signifies occurrence. c = above usual percentage. R = rounded. A = angular.

Locality.	Character of grain.	Fluorspar.	Garnet.	Magnetite.	Pyrite.	Anatase (pyramidal).	Anatase (tabular).	Cassiterite.	Rutile.	Zircon.	Hæmatite.	Ilmenite.	Tourmaline (brown).	Tourmaline (blue).	Tourmaline (tabular).	Barytes.	Brookite.
1.	R.	+	...	+	...	...	+	...	+	+	...	+	c	+	...	...	+
2.	A.	...	...	+	...	...	+	...	+	+	...	+	+	+	...	+	...
3.	A.	...	...	+	...	...	+	...	c	c	...	+	+	+	...	...	c
4.	A.	...	...	+	...	...	+	...	+	+	...	+	+	+	...	...	+
5.	A & R.	...	...	+	...	...	+	...	+	+	...	+	+	c	...	...	+
6.	A.	...	...	+	...	+	+	...	+	+	...	+	+	c	...	...	+
7.	Sub A–A.	...	...	+	...	+	+	...	c	c	...	+	+	+	...	...	+
8.	Sub A–R.	...	r	+	...	+	...	...	+	+	+	+	+	+	..	c	r
9.	R.	...	...	+	..	+	+	...	+	+	...	+	+	+	...	...	...
10.	Sub A–R.	...	...	+	...	...	+	...	+	+	...	+	+	+	+	...	...
11.	Sub A–R.	...	...	+	...	...	...	...	+	c	...	+	+	+	...	+	...
12.	R.	...	...	+	...	+	+	...	+	+	...	+	+	+	...	...	...
13.	Sub A.	...	...	+	...	...	c	...	+	+	...	+	+	c	c	+	+
14.	R.	...	...	+	...	+	+	...	+	+	+	+	+	+	...	...	...
15.	Sub A–R.	...	...	+	...	+	...	...	+	c	...	+	+	+	+	...	...
16.	R.	...	...	+	...	...	...	...	+	+	...	+	+	+	+	...	...
17.	R.	...	...	+	...	+	+	...	c	c	...	+	+	c	...	...	...
18.	Sub A–A.	...	+	+	...	...	...	...	c	c	...	c	+	r	...	...	...
19.	Sub A.	...	...	+	...	+	+	...	c	+	+	+	+	+	+	...	...
20.	Sub A.	...	+	+	...	...	...	...	+	+	...	+	+	r	...	...	...
21.	Sub A–R.	...	+	c	...	...	...	...	+	+	...	c	+	...	...	...	...
22.	Sub A–R.	...	...	+	...	...	+	...	+	c	...	+	+	+	+	...	+
23.	Sub A.	...	c	+	...	...	...	...	+	+	...	+	c	c	...	...	...
24.	A.	...	...	+	...	c	+	...	+	+	+	+	+	+	...	...	...
25.	A.	...	c	+	...	+	+	...	+	+	..	+	c	+	...	...	...
26.	Sub A–R.	...	...	+	...	...	...	...	+	+	...	+	+	+	...	...	...
27.	Sub A.	+	...	+	...	...	+	...	+	+	+	+	c	+	...	...	+
28.	Sub A.	+	...	+	...	+	+	...	+	+	...	+	c	...	...	...	+
29.	Sub A.	...	...	+	...	+	c	...	+	c	...	+	+	+	...	...	...
30.	Sub A.	...	...	+	...	...	+	...	+	+	+	+	c	...	...	?	+
31.	Sub A.	...	+	+	...	+	+	...	+	+	...	+	c	+	...	...	...
32.	Sub A.	...	+	+	...	...	...	...	+	+	...	+	c	+	...	...	...
33.	Sub A.	...	c	+	...	...	...	...	+	+	...	+	c	+	...	...	...
34.	Sub A.	...	+	+	...	+	c	?	c	c	...	+	c	+	...	...	...
35.	Sub A.	...	c	+	...	...	+	...	+	+	...	+	+	+	...	...	+
36.	A.	...	+	+	...	+	+	...	+	+	...	+	+	+	...	+	+
37.	A.	...	+	...	...	...	...	...	+	+	...	...	+	+	...	c	...
38.	A.	?	c	...	...	...	...	...	+	...	...	...	+	+	...	...	...
39.	A.	...	+	+	...	...	c	...	+	+	...	+	+	+	...	...	...
40.	Sub A.	...	c	+	..	...	r	...	+	+	...	+	+	+	r	...	...
41.	Sub A.	...	...	+	...	+	c	...	c	+	...	+	+	c	r	...	r
42.	Sub A.	...	c	+	...	+	c	...	+	+	...	c	+	r	...	...	+
43.	Sub A.	...	r	+	...	r	c	...	+	+	...	c	+	+	...	...	+
44.	Sub A.	...	...	+	...	r	c	...	+	+	...	c	+	+	r	+	...
45.	Sub A.	...	+	+	...	+	+	...	+	+	...	+	+	+	...	...	...
46.	Sub A.	...	+	+	...	+	c	...	+	+	...	c	+	r	...	...	+
47.	Sub A.	...	+	+	...	...	+	...	+	+	...	c	+	r	...	...	...
48.	Sub A.	...	+	+	...	...	+	...	+	+	+	+	+	+	...	...	...
49.	Sub A–A.	...	c	+	+	...	...	...	+	+	...	+	+	+	...	...	...

species in the New Red Sandstone.

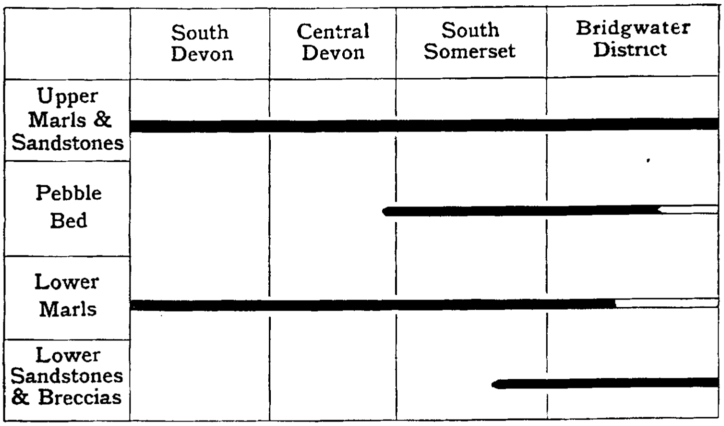
r = below usual percentage. ? = occurrence doubtful. Sub A = subangular.]

Cordierite.	Sillimanite.	Staurolite.	Topaz.	Actinolite.	Biotite.	Chlorite.	Muscovite.	Orthoclase.	Sphene.	Cyanite.	Microcline.	Plagioclase.	Leucoxene.	Pinite.	Serpentine.	Shimmer-aggregates.	
...	...	c	...	...	+	+	+	+	...	...	+	+	c	...	+	+	Lower Breccias.
...	...	+	...	...	c	+	+	+	+		+	+	+	...	...	...	
...	...	+	...	...	+	+	+	+	...	...	...	...	c	...	...	...	
...	...	+	...	...	...	+	+	+	...	...	..	...	+	...	+	+	
...	+	+	+	...	+	...	+	+	+	...	...	+	c	...	+	...	
...	...	+	...	...	+	+	+	c	+	...	+	c	+	...	...	...	
...	...	c	...	...	...	+	+	+	+	...	+	+	c	...	...	...	
...	...	+	...	...	...	+	...	r	...	...	...	...	...	...	...	...	
...	+	+	...	...	...	+	+	+	+	...	+	+	+	...	...	+	Lower Sandstones.
...	...	+	...	...	...	...	...	+	...	...	+	+	+	...	...	...	
...	...	...	...	...	+	+	+	...	...	...	...	...	c	...	...	+	
...	...	+	...	...	...	?	+	c	+	...	+	+	c	?	...	+	
...	...	+	...	...	...	+	+	+	+	...	...	+	+	...	+	...	
...	...	+	...	...	...	...	+	+	...	...	+	c	+	...	...	...	
...	...	+	...	...	...	...	+	+	...	...	+	+	+	?	...	+	
...	...	+	...	...	...	...	+	+	+	...	c	+	+	...	...	...	
...	...	+	...	...	...	+	+	+	...	...	...	+	+	...	...	...	
r	...	+	...	...	...	...	...	+	...	...	...	...	+	...	...	...	
...	...	+	...	...	...	...	+	+	...	...	...	...	+	...	...	+	
...	...	+	...	...	...	...	...	+	...	...	...	...	+	...	...	...	
...	...	c	...	..	...	...	...	+	...	...	...	...	+	...	...	...	
...	+	+	...	...	...	+	+	...	+	...	...	...	+	+	+	+	Lower Marls.
...	...	+	...	...	...	+	+	+	+	...	+	+	+	?	...	...	
...	...	+	...	...	...	...	+	+	+	...	...	?	...	...	...	...	
...	...	+	..	...	...	...	+	c	...	...	+	+	+	...	...	...	
...	...	+	...	...	...	+	+	+	+	...	+	+	+	...	...	...	
...	+	c	...	...	+	+	+	+	+	...	+	+	c	...	+	c	Pebble-Bed.
...	...	c	...	...	...	...	c	+	?	...	+	+	+	...	...	+	
...	?	c	...	...	+	+	c	+	...	?	+	+	+	+	+	+	
...	...	c	...	...	c	c	+	+	...	...	+	+	+	...	...	+	
...	...	c	...	...	+	+	+	+	+	...	+	+	+	...	...	+	
...	...	c	+	...	...	...	+	+	...	...	+	+	+	...	...	+	
...	...	c	...	...	...	...	c	+	...	...	+	+	+	...	...	+	
...	...	c	...	...	...	+	+	+	+	+	+	+	c	...	...	+	
...	...	+	...	...	+	+	c	+	...	+	+	+	+	+	+	+	Upper Marls, Sandstones, and Upper Keuper Sandstones.
...	...	+	...	...	...	...	+	+	...	...	?	?	+	...	...	...	
...	...	...	...	...	...	...	+	+	+	...	?	?	?	...	...	...	
...	...	...	...	+	...	...	+	+	+	...	?	?	+	...	...	...	
...	+	...	...	...	+	...	c	+	+	...	+	+	+	+	+	+	
...	...	+	...	...	...	+	+	+	...	...	...	...	+	...	...	...	
...	...	r	...	...	...	...	+	+	...	...	+	+	+	...	...	...	
...	...	r	...	...	...	...	+	+	...	...	r	...	+	...	...	...	
...	...	+	...	...	+	+	+	+	...	...	...	...	+	...	...	...	
...	...	+	...	...	...	...	...	+	...	...	...	+	+	...	...	...	
...	...	r	...	...	...	...	...	+	...	...	...	...	+	...	...	...	
...	...	+	...	...	...	...	...	r	+	...	...	...	+	...	...	...	
...	...	r	...	...	...	...	...	r	+	...	...	...	+	...	...	...	
...	...	+	...	...	...	+	...	r	...	...	...	...	+	...	...	+	
...	...	+	...	...	...	...	...	+	...	...	...	...	+	...	...	...	

It will at once be seen from Table I that, although there is a general similarity in the mineral contents of the various divisions of the New Red, it is possible to observe radical differences, which become more apparent the more closely the rocks are studied.

The distribution of garnets shown in Table II (below) brings out clearly how, not only various horizons in the New Red, but also the same horizons in different districts, may exhibit special mineralogical characteristics. The same point may be urged with reference to the distribution of staurolite, tourmaline, and several other minerals.

Table II, *illustrating the vertical and horizontal distribution of garnet in the New Red rocks.*



There are, however, a certain number of mineral species which are present in almost every sediment, and thus by themselves throw but little light on the origin of a deposit; at the same time, the relative abundance of any mineral at different localities on the same horizon is most important.

To sum up the results expressed in the two tables given above, it may be stated that the Lower Breccias and Sandstones are fairly constant as to their mineral contents. In the extreme south of Devon they approximate in composition more closely to the southern part of the Pebble-Bed: for staurolite is common, and fluorspar also occurs, in both. They contain, and are characterized by, an unusually large quantity of iron-ores, brookite, rutile, felspars, and felsitic material, but above all by the abundance of blue acicular tourmaline, either free or embedded in quartz. Most of the quartz gives uniform extinction, and there is, in South Devon, a total absence of garnets. In Somerset, however, garnets are fairly common in the Lower Sandstones around the inliers of Cannington and Quantock.

In the Lower Marls much more of the quartz shows undulose extinctions; blue acicular tourmaline becomes less frequent, but the brown stumpy prisms of this mineral are more common; brookite is scarce, and iron-ores are less abundant. In South Devon garnets first appear on this horizon (Table II).

The Pebble-Bed in Devon and Somerset presents two more or less distinct types: one existing from the south coast to the neighbourhood of Uffculm, the other obtaining from Uffculm northwards. It will be convenient to refer to these respectively as the southern and the northern type. Both types are bound together by the prevalence of staurolite, and they may be compared and contrasted as follows:—

Southern type.	*Northern type.*
Staurolite abundant.	Staurolite abundant.
Blue tourmaline rare.	Blue tourmaline more common.
Brookite rare.	Brookite more common.
Garnets absent.	Garnets present.
Fluorspar present.	Fluorspar absent.
Ferruginous cement.	Ferruginous and calcareous cement.

All along its course the Pebble-Bed contains many minute fragments of schistose material; and much of the quartz, especially in the south, has undulose extinction.

The Upper Marls and Sandstones, from south to north, are characterized by an abundance of pink garnets and the general occurrence of brookite; and in the south more especially by the occasional presence of actinolite. Staurolite is not so abundant in these rocks as in the Pebble-Bed, and, in addition, it is in these upper beds that we most usually meet with such cementing-materials as barytes, celestine, and gypsum in quantity. Barytes, however, occurs less plentifully at certain localities on other horizons, both in the Red rocks of this district and in those of the Midlands.

V. Conclusions.

A most important factor in the study of these sediments is the relation that they bear to the pre-existing rocks of the West of England. In dealing with this subject several questions arise, the most prominent of which is—What rocks were capable of yielding the material which entered into the composition of the New Red Sandstone? There is no doubt that most of the older rocks, now exposed at the surface, supplied detritus; but it does not appear possible, as pointed out in my previous paper, for them to have furnished all the mineral species detected in the heavy residues.

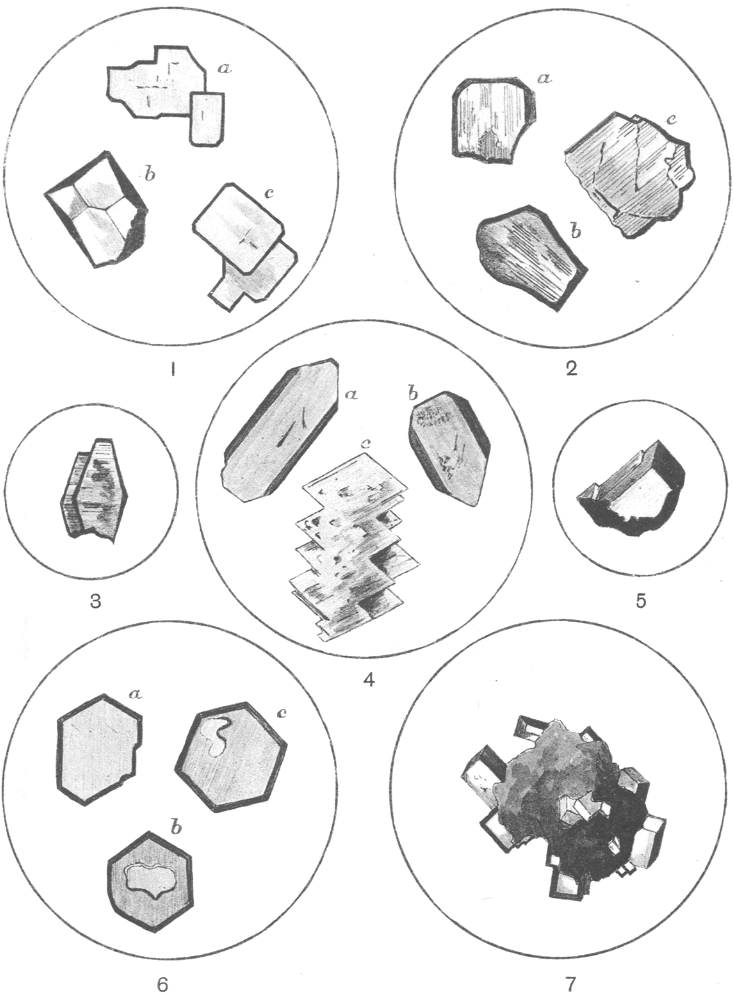
In the Lower Breccias and Sandstones staurolite occurs most plentifully in the southernmost exposures; and, taking into consideration the evident local origin of these deposits, as proved by the larger rock-fragments, it seems safe to assume that they were laid down not far from a series of staurolite-bearing rocks. No such rocks, however, exist in this part of England, but, as previously suggested, probably lay to the south of the present coast-line.

From a study of the distribution and quantity of certain mineral species, it is possible in most instances to gather some idea of the relative amounts of material derived from various sources. This is more especially true in the case of the Lower Breccias and Sandstones and the Pebble-Bed. The material forming the marls, however, as might be expected from its finely comminuted nature, appears to have been supplied from all directions, and by a greater variety of rocks than those yielding detritus towards the formation of the other New Red sediments.

With regard to the source of the various mineral species it is most difficult to speak, except in certain cases; but, so far as can be judged, all the minerals detected in the New Red deposits, with the exception of staurolite, could be supplied by the older rocks of the West of England. The greater abundance of such minerals as blue tourmaline, topaz, rutile, and brookite appears to indicate that the rocks in which they occur were largely derived from the granite-masses of Devon and Cornwall, but more especially points to their attendant metamorphic rocks and veinstones.

The garnets of the New Red deposits are clearly in no way dependent on the distribution of staurolite, but, on the contrary, are of most frequent occurrence in the northern part of the district where staurolite is less abundant. The fact that garnet, in the Pebble-Bed, makes its appearance together with an increased proportion of blue tourmaline, points to its derivation, at any rate in part, from the metamorphic rocks surrounding the West of England granites. Its absence from certain horizons might be accounted for, either by the direction of the sediment-bearing currents, or by the extremely local occurrence of garnets in the metamorphic aureoles of this district. It is only where subordinate calcareous bands of the Devonian and Carboniferous rocks and diabase-intrusions come within the influence of the granites that this mineral has been produced. It is not suggested that all the garnets in the New Red rocks were supplied by these metamorphic areas; but, should it be so, it would appear from the distribution of this mineral that all the New Red rocks of North Devon and West Somerset were formed in part of material carried from the west and south-west.

The Lower Breccias have always been considered as deposits derived from sources near at hand, for, as pointed out by De La Beche, Godwin-Austen, Conybeare & Phillips, and Mr. R. H. Worth, among the rock-fragments found in them are numerous examples of well-known rock-types present in Devon. The minerals and grains forming the finer material of these deposits point towards the same conclusion; but, in addition, especially in South Devon, they suggest strongly the influence of certain rock-masses non-existent within the south-western area as now known. There is, also, nothing in the finer material to prove that the granite-masses themselves were undergoing denudation at the time when the Lower Breccias were being deposited.



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MINERALS FROM THE NEW RED SANDSTONE, ETC.

The climatic conditions[1] under which the Lower Breccias and Sandstones were deposited have been discussed for these and similar rocks. The idea of the existence of desertic and lateritic conditions[2] is, it seems, made more tenable when we consider the prevalence of millet-seed sands and the increased proportion of plagioclase-felspars[3] in these deposits.

The Lower Marls, and the Upper Sandstones and Marls, as regards composition, appear to be the most uniform members of the New Red Sandstone, a fact explained partly by their lithological character and partly by their mode of deposition. As stated before, they have evidently had a more complex source than the other members of the New Red, and were deposited chiefly from sediment-bearing currents which had no constant direction for any length of time.

Again, in the case of the Upper Sandstones and Marls it is most difficult, in view of their transgression northwards and westwards on to older rocks, to say how much of the material of which they are composed is of direct origin from the parent source, and how much has been derived from pre-existing New Red deposits.

Such problems will only be possible of solution when the petrology of the older sedimentary rocks has received adequate attention.

In conclusion, I wish to express my indebtedness to Prof. Sollas for much assistance and encouragement during the early stages of this work; to Mr. Ralph Morgan and Mr. Robert Hancock, of Exeter, as also to Mr. W. G. Churchward, F.G.S., of Teignmouth, for their kindness in collecting for me many samples of the New Red rocks; and to Mr. Ussher, F.G.S., for allowing me to work on material collected by him in Somerset.

EXPLANATION OF PLATE XII.

Fig. 1 *a*. Anatase: group of crystals in parallel growth, tabular parallel to the base $\{001\}$, from the Pebble-Bed of Newton Poppleford (Devon). × about 115. (See pp. 231–32.)

1 *b*. Anatase, with low pyramids of such form as $\{h\,h\,l\}$, from the Lower Breccias of the Ness, Teignmouth (Devon). × about 100. (See p. 232.)

1 *c*. Anatase similar to fig. 1 *a*, from the Lower Sandstones of Honiton Clyst (Devon). × about 200. (See pp. 231–32.)

2 *a*. Brookite, pale-yellow crystal from the Lower Breccias of the Ness, Teignmouth (Devon). × about 250. (See p. 238.)

2 *b*. Brookite, an almost colourless, somewhat rounded crystal, from the Lower Marls of Raddon Quarry, near Thoverton (Devon). × about 250. (See p. 238.)

2 *c*. Brookite, an almost colourless crystal, from the Lower Sandstones of Monkerton, near Pinhoe (Devon). × about 1000. (See p. 238.)

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[1] J. G. Goodchild, Trans. Geol. Soc. Edin. vol. vii (1893–99) p. 203; and J. A. Phillips, Quart. Journ. Geol. Soc. vol. xxxviii (1882) p. 110.

[2] J. J. H. Teall, Proc. Geol. Assoc. vol. xvi (1899) p. 148.

[3] W. Mackie, Trans. Geol. Soc. Edin. vol. vii (1893–99) p. 443; see also T. G. Bonney, Proc. Liverp. Geol. Soc. vol. ix, pt. ii (1902) p. 220.

Fig. 3. Anatase, steeply pyramidal, with small basal plane, from the Pebble-Bed of Woodbury Castle (South Devon). × about 150. (See p. 232.)

4 *a*. Staurolite, an almost perfect crystal showing the forms {010}, {110}, {101}, and {001}, from the recent blown sands of Newgale (Pembrokeshire). × 100. (See pp. 234–35.)

4 *b*. Staurolite, similar crystal to the foregoing, from the Pliocene deposits of Lenham (Kent). × about 100. (See pp. 234–35.)

4 *c*. Staurolite, grain bounded by cleavage-faces, the most usual mode of occurrence in the Red rocks of the West of England and the Midlands, from the Pebble-Bed of Budleigh Salterton (Devon). × about 100. (See p. 234.)

5. Anatase, imperfect octahedral crystal with moderately large basal plane, from the Lower Breccias of the Parson and Clerk Rocks, Teignmouth (Devon). × about 150. (See p. 232.)

6 *a*, *b*, *c*. Tourmaline, blue hexagonal crystals flattened parallel to the base, and modified by narrow rhombohedral planes, from the Lower Sandstones of Monkerton, near Pinhoe (Devon). × about 100. (See p. 233.)

7. Anatase, tabular crystals growing on decomposing ilmenite from the Keuper Sandstone of Weston (Cheshire). (From a preparation supplied by Mr. J. B. Scrivenor, M.A., F.G.S.) × about 100. (See p. 232.)

Discussion.

Dr. J. W. Evans laid stress on the importance of work on sand-grains. He suggested that the tabular crystals of anatase might be cleavage-plates following the perfect basal cleavage.

Mr. G. Barrow remarked on the interest of the Author's table showing the distribution of the minerals at different horizons. In the lowest beds, blue schorl-needles seemed especially abundant; these were of local origin, as one would rather expect. Higher in the series staurolite became common; but this mineral was not of local origin, being possibly derived from the rocks in which the adjacent English Channel (clearly a submerged valley) had been cut. These rocks were almost certainly, in the main, pre-Cambrian and metamorphosed. There was a possible doubt as to the origin of the garnets: their local source, in part at least, would be proved by the presence of the pneumatolytic type, with the characteristic well-marked banding, or parallel planes of growth. Were such garnets found in the sediments examined by the Author?

The President (Prof. Sollas) complimented the Author on the successful manner in which he had brought the skill of the mineralogist to bear on the interpretation of these minute constituents of sedimentary beds. The paper was of interest, not only for its numerous observations in detail, but for its general conclusions; and he would like to enquire whether the Author still looked to Armorica as the source of some of the minerals that he had determined.

The Author thanked the previous speakers for their kind remarks relative to his work, and, in reply, stated that although in some instances tables of anatase might be produced in the manner suggested by Dr. Evans, in the New Red rocks there were sufficiently numerous instances of tabular crystals growing on ilmenite, and crystals showing very low pyramid-planes, to preclude the possibility of the tabular crystals being due to cleavage only.

In reply to Mr. Barrow, he remarked that the blue acicular tourmaline was not confined to the lower divisions of the New Red Sandstone, but was exceptionally abundant in the Lower Breccias and Sandstones. Most of the garnet in these deposits appeared to be a pale-pink variety of that mineral, such as was usually met with in true contact-deposits. He could not definitely state that he had recognized any garnets to which a pneumatolytic origin could be assigned.

With reference to the remarks made by the President, he said that, while it was possible to derive most of the minerals and grains from rocks known to occur in the West of England, it was impossible to regard the staurolite as having come from that district. The parent rock of this mineral certainly lay to the south of the present coast-line of Devon, and, as contended in his earlier paper, in the old land-area of Armorica.