12. *The NATURE and ORIGIN of the PLIOCENE DEPOSITS of the COUNTY of CORNWALL, and their BEARING on the PLIOCENE GEOGRAPHY of the SOUTH-WEST of ENGLAND.* By HENRY BREWER MILNER, M.A., D.I.C., F.G.S., Lecturer in Oil Technology at the Royal School of Mines. (Read December 21st, 1921.)

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I. INTRODUCTION.

THE present paper deals more particularly with the petrography of the younger Tertiary deposits of Western Cornwall which, by reason of their mode of occurrence and lithological similarity to the well-known fossiliferous beds of St. Erth, have been generally assigned to the Pliocene age. These deposits occur as isolated patches of detrital material resting in eroded hollows in Palæozoic or older rocks in the south-western part of the county, and are located at St. Agnes, 4 miles due south-west of Perranporth; at St. Erth and Canons Town in the Hayle-River valley; at Crousa Common, a mile and a half south-west of St. Keverne (Lizard district); and at Polcerebo, near Crowan, 4 miles south of Camborne, where an outcrop of gravels of alleged Pliocene age is found. With the exception of the St. Erth Beds, no fossils have hitherto been discovered in these deposits, and their stratigraphical position has been inferred entirely from general geological and topographical considerations.

The object of this paper is not only to establish the relative ages of these deposits by petrographic methods, but to demonstrate the importance of this mode of attack in problems of stratigraphical correlation where palæontological evidence is in some cases lacking. In addition, the mineralogical factors concerned are used as a guide to the determination of the origin of these sediments and, in conjunction with topographic data, to restore the geography of this part of Britain in early Pliocene times, in so far as the evidence at our disposal allows.

II. MODE OF OCCURRENCE OF THE DEPOSITS.

(a) St. Agnes.

Flanking the northern part of St. Agnes Beacon, and having the form of a crescent-shaped outcrop, the Pliocene deposits are here resting on a belt of metamorphosed Ladoek Beds (Lower Devonian) surrounding the St. Agnes granite-mass, except in the extreme south-western corner where they abut on the granite itself. The height of the Beacon is 628 feet O.D., and, as we descend the northern slope, the deposits are first met with approximately along the line of the 420-foot contour, whence they are continuous down a gentle gradient to the 350-foot level. Both the upper and the lower limits of the outcrop are concealed by several feet of 'Head,' a conspicuous feature of the Quaternary geology of this region, and consequently the actual contacts between the sands and the underlying rocks are everywhere hidden.

In addition to several minor natural exposures of the sands and clays, which here, as elsewhere, constitute the principal facies of these deposits, there are several overgrown pit-sections visible; while two more recent pits giving greater facilities for study occur: one at Higher Bal, half a mile west of St. Agnes Church, and the other at Beacon Cottage, at the foot of the Beacon on the south-western side. In the former case about 12 feet of clay and sand are now seen overlain by 3 to 4 feet of 'Head'; in the latter exposure only 10 feet of grey clay are seen, the section being now much obscured. The older sections mentioned by Sir Henry De la Beche¹ and quoted by Clement Reid² are certainly no longer in existence, and are either quite overgrown or obliterated by waste-material thrown out from the adjacent mines.

(b) St. Erth.

On the eastern side of the Hayle-River valley, and situate about half a mile from the river itself, at the village of St. Erth, is the classic occurrence of Pliocene deposits, so well known for their peculiar (indeed, in this country, unique) fauna. The actual boundaries of the outcrop are again somewhat difficult to define precisely, on account of the thick capping of 'Head' developed. Roughly elliptical in shape, about half a mile long and a quarter of a mile broad, the St. Erth sands lie on a gentle valley-slope between the 170- and the 50-foot contours; the mass has a discernible north-easterly and south-westerly strike, and is bounded by a well-marked quartz-porphry dyke ('Mellaneer' or 'Long-Rock' elvan)³ on the north-west, and by an elongated sill of greenstone on the south-east, both intrusions having this dominant

¹ 'Report on the Geology of Cornwall, Devon, & West Somerset' 1839, pp. 258-60.

² 'The Pliocene Deposits of Britain' Mem. Geol. Surv. 1890, pp. 66-67.

³ 'The Geology of the Land's End District' Mem. Geol. Surv. 1907, pp. 63-64.

strike direction. Between the dyke and the sill is the basin-shaped depression in the Mylor Slates (Lower Palæozoic) in which the deposits were laid down, and thus we can explain the disposition of the sands in a north-easterly and south-westerly direction at this place. Natural sections in these deposits are rare, and evidence for mapping has to be based largely on quarry-exposures, on the character of the soil, and on topographic data. The artificial sections at present visible differ greatly from those examined even 14 years ago, when the Geological Survey Memoir of the district was first published; in no case is the fossiliferous clay to be seen now, and, of the three exposures available for study, that of the Cornish Sand Company's pit (an enlargement of the better known 'Harvey's Pit')¹ is by far the best. This pit is situated immediately south of and adjacent to the road leading from the village to the vicarage. The old pits west of the vicarage, in which the fossils were originally obtained, are now much overgrown, and all traces of the fossiliferous clays obscured.²

The Cornish Sand Company's pit, which has been rapidly extending during the last few years, shows an excellent section in the Pliocene sands. The character of these deposits varies considerably both laterally and in depth, and apart from minor irregularities in bedding, there is a marked dip of the whole series of 5° north-westwards which determines the gentle slope of the fields between the vicarage and the village, and further explains the non-appearance of the fossiliferous clay in this pit. The section shows an average thickness of 20 feet of sand resting upon the eroded Palæozoic floor, which consists of slate intersected in one place by an 'elvan' dyke. The sand is overlain by 2 to 4 feet of 'Head' and surface-soil.

The late Clement Reid, writing in 1890,³ suggested that possibly a similar outcrop to that of St. Erth would be ultimately discovered on the watershed separating the Hayle River from the streams draining into Mounts Bay at Newtown; but careful search, both here and at likely horizons throughout the whole valley from north to south, failed to reveal any trace of Pliocene material other than that recorded by the Geological Survey as occurring at Lelant Downs, half a mile north of Canons Town, 2 miles west-north-west of St. Erth. In this case the evidence of outcrop, though indefinite, is certainly in favour of the occurrence of a small patch of Pliocene deposit resting upon metamorphosed Mylor Slate at a height of about 150 feet above O.D., and having much the same topographical aspect as the St. Erth Beds opposite. No pits have ever been dug in this deposit, and the only evidence obtainable is from the sandy nature of the soil and from a few blocks of ferruginous sandstone found occasionally on the valley-slope.

¹ Mem. Geol. Surv. 1907, p. 72.

² At least 5 feet of sand and rubbly surface-material now filling the pits would have to be removed before exposing the clay again, even if the thick and overgrown vegetation were cleared.

³ 'The Pliocene Deposits of Britain' Mem. Geol. Surv. p. 60.

(c) St. Keverne.

Resting on the Lizard 'platform' at a height of 364 feet above O.D., and situated a mile and a half due south-west of the village of St. Keverne, are the Crousa-Common gravels first noticed by Sir Henry De la Beche in his report of 1839. Unlike the similar deposits of St. Agnes and St. Erth, the extent of this outcrop is easy of definition. It consists of a rectangular mass 1 mile long by half a mile broad, lying upon the eroded surface of the Lizard gabbro, the conspicuous feature of this area. As Mr. J. B. Hill has pointed out,¹ the extent of the deposits is naturally defined by the sharp change in vegetation noticeable as the boundaries between the sands and the igneous rocks are traversed; in the former case the marked development of gorse, heather, and pine contrasts strongly with the more fertile grassy soil yielded by the gabbro, and the typical weathered blocks of this rock scattered everywhere over the surface of its outcrop constitute a further element of differentiation between the two.

Both natural and artificial sections in these sands are common, but only one pit is at present worked, the others being overgrown and often under water. The best exposure is that in a shallow quarry adjoining the main road to St. Keverne, immediately east of the 9th milestone from Helston. This pit shows a section of coarse sands and gravels varying from 8 to 10 feet in thickness, and capped by a few inches of mixed surface-detritus and peaty soil. The deposits are remarkable for their varying texture, the strong current-bedding exhibited, and for the quantity of big pebbles and even boulders associated with them. Their base is not seen in this particular pit, although it cannot be far below the floor of the present working (1920), as in wet weather the pit is badly flooded, pointing to the existence of impervious clayey rock at no great depth, such as would be yielded by the superficial decomposition of the gabbro. In some of the older abandoned pits on the north side of the road in the wood, blocks of gabbro may be seen in dry weather protruding from underneath the sandy floor, thus showing the vertical extent of the deposits.

No fossils have ever been found in the Crousa-Common deposits, and their Pliocene age has been inferred from their relations to the Lizard 'platform,' a remnant of the characteristic Pliocene features of the West Country.

(d) Polcrebo.

The curious pebble-bed found at Polcrebo near Crowan, 4 miles south of Camborne, originally described by W. Tyack² and later referred to by Mr. J. B. Hill,³ is of very limited extent; it consists principally of well-rounded pebbles of quartz, resting at a height

¹ 'The Geology of the Lizard & Meneage' Mem. Geol. Surv. 1912, p. 230.

² Trans. Roy. Geol. Soc. Cornwall, vol. ix (1875) p. 177.

³ 'The Geology of Falmouth & Camborne' Mem. Geol. Surv. 1906, pp. 88-89.

of 480 feet upon an eroded granite-surface, and is of very obscure origin. Beyond the doubtful topographical evidence as to its alleged Pliocene age, there is little whereby to reconcile its suggested relationship to the St. Agnes, St. Erth, or Crousa-Common deposits.¹

III. METHODS OF INVESTIGATION.

In all cases the individual outcrops of the deposits were sampled both laterally and vertically: in the first instance, suitable exposures were located along the strike of the beds, from which samples were taken at regular intervals if outcrops allowed; in the second case all the principal quarry-sections at each locality were visited, and the sands sampled from top to bottom at intervals depending on the lithological variations noted in the beds. As an example of this method of procedure we may take the St. Erth occurrence—in a lateral distance of some 800 yards measured along the strike of the beds, four samples were taken at approximately equal intervals of 200 yards, the material being furnished by stream, hedgebank, and quarry. For sampling in depth, the Cornish Sand Company's pit was chosen, since it showed the maximum vertical section exposed in the beds at the time. In this case samples were taken from 6, 8, 14, 20, 22, and 23 feet below the surface, these horizons representing the more marked lithological variations in the deposit as seen in this pit. The samples referred to in all instances consisted of about 200 grammes of material, having regard to the average grade-size of the particles, about 0·2 mm. In the case of much coarser material, as at Crousa Common, at least 500 grammes were taken for each sample, in order to ensure a reasonable yield of 'heavy' residue.

The usual method of procedure for the qualitative examination of the mineral constituents of the deposits was adopted; the samples were first sifted free of the larger grains and pebbles, by using a 30-mesh sieve and later a 60-mesh sieve; in this way each sample was divided into three rough grades, a coarse, medium, and fine. The coarse material, rejected by the 30-mesh sieve, included the grains greater than approximately 0·5 mm. in diameter; the medium material, passed by the 30-mesh but rejected by the 60-mesh sieve, included the grains between approximately 0·25 mm. and 0·5 mm., while the fine material, passed by the 60-mesh, included all fine sand, silt, and clay: that is, particles less than 0·25 mm. in diameter. It is desirable to emphasize that such grading is only of a very approximate character, and is used solely for convenience in qualitative work, but not for accurate mechanical analysis, which must be obtained by the ordinary methods of elutriation; it is of use, however, in giving a rough impression of the relative proportions of the particles between the chosen limits.

¹ *Ibid.* p. 88; also Trans. Roy. Geol. Soc. Cornwall, vol. ix (1875) p. 181.

The coarse material was first carefully examined with a lens, and subsequently with the microscope, in the latter case by placing some of the grains on a black card and viewing them by reflected light. The medium and fine material were both washed with water, treated with a dilute solution of hydrochloric acid so as to remove any ferruginous coating of the grains, and in the case of the fine grade, boiled previously with a 1 per cent. solution of sodium carbonate to deflocculate silty and clayey matter. The clean sand was then dried, and about a third taken for treatment with 'heavy' liquids. (A preliminary trial in all cases showed that these Pliocene deposits yielded abundant residue, and consequently there was no necessity for utilizing the whole of the cleaned sample, except for quantitative determination.)

For the 'heavy' mineral concentration bromoform of specific gravity 2.82¹ and, in special circumstances, cadmium borotungstate of specific gravity 3.28 were used. The residues thus obtained were separated with an electromagnet into magnetic and non-magnetic crops; these were then mounted in Canada balsam for microscopical examination, and a slide was made in each case of the 'light' material of the sample, s.g. < 2.82. The total amount of 'heavy' mineral concentrate obtained in all cases was mounted, to ensure inclusion of the rarest mineral species present in the sediment.

In many instances the samples were examined quantitatively, and the percentages of light material, ferruginous cement, silt and clayey matter, and 'heavy' residue determined. Such results are included below in the section dealing with the petrography of the various deposits.

IV. LITHOLOGICAL CHARACTER OF THE DEPOSITS.

(a) St. Agnes.

The deposits here consist of a well-marked series of yellow, white, and brownish-red sands overlain by grey and mottled clays. The principal section exposed at Higher Bal, west-north-west of St. Agnes Church, shows about 6 feet of sand, yellow at the base, and passing up into an almost pure white sand, which gives place to a brownish-red facies immediately beneath the clay. The transition from the sand to the clay is actually not so sharp as at first sight appears, and an intermediate arenaceous clay separates the sands below from the true clays above. The sandy clay and overlying grey and mottled clays in this section vary from 7 to 8 feet in thickness, although this facies tends to thicken south-westward; as in the Beacon Cottage pit no sand is exposed, and 8 to 10 feet of clay occur. The sands themselves occasionally

¹ Since the War, the bromoform put on the market has varied considerably in purity, and the specific gravity has fluctuated accordingly; in some cases it was possible to raise the gravity to 2.9 by repeated distillation, but not without great trouble and a certain amount of loss.

yield interesting well-worn quartz-pebbles, quartz-veined 'killas' pebbles, rounded schorlaceous fragments, and (more rarely) rounded pebbles of cassiterite.¹ A few coarser grit-bands are present in the red sand, but they are essentially local and discontinuous.

(b) St. Erth.

Here again the clay and sand facies are both developed in these deposits, although unfortunately we are no longer able to study the former *in situ*; for the old section in the Vicarage pit at St. Erth, in which the fossiliferous clay occurred (see p. 351), we must refer to Prof. P. F. Kendall & R. G. Bell's diagram in their paper dealing with the Pliocene fauna of this deposit.² From the details given it is evident that the section showed a few feet of 'Head' capping about 6 feet of yellow sand overlying the clay; the latter rested upon a much thicker band of 'fine quartzose sand' persistent to the base of the series. Unfortunately, the authors of this paper omitted all details as to thickness of these beds; but, from particulars given by Clement Reid,³ and from the section which it is now possible to measure in the uppermost yellow sand at the Vicarage pit, it would seem that the clay varied from 7 to 8 feet in thickness, and the underlying sand from 10 to 12 feet in thickness. The pit now only shows about 5 feet of the uppermost yellow sand.

The St. Erth sands vary lithologically in much the same manner as those of St. Agnes do: the same yellow, white, and brownish-red facies, with an associated grit-band, are present, and the last-mentioned contains several small pebbles of quartz, killas, greenstone, and schorlaceous material; this grit-band, although quite conspicuous where it does occur, is non-persistent and of little value as a definite horizon. Other seams of pebbles are scattered promiscuously throughout the red sand; such pebbles are always well worn and by far the greater percentage consists of quartz. A loamy sand underlying the grit-band is a well-differentiated facies, of a consistency contrasting markedly with the white and yellow sand above; it constitutes the best moulding-sand from the pit, and is of importance on that account. Current-bedding in this series is not a well-marked feature, although it may be detected in some instances on a small scale; in this respect, we may note a further similarity to the St. Agnes deposits. On the whole, the St. Erth deposits are of finer texture than those of St. Agnes or St. Keverne, particularly the last-named; their general lithology suggests deposition in deeper water than in the other cases.

The lithological character of the deposit alleged to occur on the opposite side of the valley at Lelant Downs, has already been mentioned (p. 351).

¹ 'The Geology of the Country around Newquay' Mem. Geol. Surv. 1906, p. 64.

² Q. J. G. S. vol. xlii (1886) fig. 1, p. 202.

³ 'The Pliocene Deposits of Britain' Mem. Geol. Surv. 1890, pp. 59 *et seqq.*

(c) St. Keverne.

In the Crousa-Common gravels there is a much wider variation noticeable, and the deposits are coarser and more heterogeneous in composition than in the preceding cases. The material consists largely of subangular fragments of quartz, occurring both as grains 0.25 mm. in diameter and as pebbles 2 or 3 inches in diameter, with every intermediate grade present; associated with the quartz are pebbles of slate of the 'killas' type, schorlaceous fragments, and pebbles of rocks recognizable in the Lizard series. Impersistent seams of finer sand and occasionally grey clay accompany the gravels, but they are by no means common. Reference must be made to the contortions and local folds exhibited by these gravels: this feature is certainly most striking in the pit adjacent to the main St. Keverne road (p. 352); but it would seem to be more easily explicable as due to current-bedding of coarse detritus in shallow water, than as the result of later subsoil movements.¹ The coarse texture and the very mixed character of these deposits tend to accentuate such inequalities of bedding; but, when examined closely, their true neritic character is quite apparent. The amount of material that has to be sifted in order to produce a sand concentrate for petrographical investigation is more than double that used in the other cases; this in itself bears testimony to the nature of these gravels.

(d) Polcrebo.

Mr. J. B. Hill has already pointed out a similarity existing between the Polcrebo gravels and those of Crousa Common, in so far as the quartz-pebbles are concerned, a feature remarked by W. Tyack in his original description of the former deposit.² The greater mass of the Polcrebo material is quite unlike that of Crousa Common, however, and consists of well-worn rounded pebbles of quartz and granite, the latter of local origin. These pebbles are extremely variable in size; Tyack says that 'they are of all sizes, from boulders as large as a pumpkin to pebbles as small as hazel-nuts.' Sand in association with the gravels is of rare occurrence, and what fine-grained material (2 mm. in diameter) there is, has been derived solely from the weathering and disintegration of the pebbles themselves. But for their elevation at 480 feet above sea-level, there is little lithologically to suggest a relationship to the deposits under consideration, although their mode of occurrence is certainly significant.

¹ 'The Geology of the Lizard & Meneage' Mem. Geol. Surv. 1912, p. 230.

² Trans. Roy. Geol. Soc. Cornwall, vol. ix (1875) p. 175.

V. PETROGRAPHY OF THE SEDIMENTS.

(a) St. Agnes.

The determination of the mineralogical composition of the St. Agnes deposits yielded the following results:—

	Horizon	I.	II.	III.	IV.
Light Material: S.G. < 2.82.	Minerals.	Essential constituent throughout. Essential authigenous material.			
	Quartz				
	Kaolin				
	Muscovite				
	Glauconite				
Heavy Residue: Magnetic. S.G. > 2.82.	Ferruginous cement				
	Magnetite	7	7	7	7
	Ilmenite	5	5	5	5
	Garnet	—	—	—	—
	Tourmaline	8	8	8	8
	Staurolite	3	1	3	3
	Epidote	4	4	—	4
	Chlorite	1	2	2	2
Heavy Residue: Non-Magnetic. S.G. > 2.82.	Biotite	1	2	2	2
	Leucoxene	7	7	7	7
	Zircon	4	6	5	5
	Kyanite	6	5	1	6
	Anatase	—	—	2	2
	Rutile	2	4	2	2
	Brookite	—	—	—	—
	Topaz	4	5	5	5
	Andalusite	7	5	8	7
	Muscovite	5	5	6	5
	Corundum	—	—	?	?
	Cassiterite	1	—	1	1
	Xenotime	?	—	? 1	? 1

[9 = 'Flood' of a particular species. 8 = Very abundant. 7 = Abundant.
6 = Very common. 5 = Common. 4 = Scarce.
3 = Very scarce. 2 = Rare. 1 = Very rare.]

- I. Yellow Sand. Base of series now exposed, 15 feet below the surface, quarry at Higher Bal.
- II. Red Sand. 12 feet below the surface, quarry at Higher Bal.
- III. 'Candle Clay.' Average of several samples taken laterally, including quarries at Higher Bal and Beacon Cottage.
- IV. Average composition of the St. Agnes deposits.

The residues yielded by all the members of the St. Agnes deposits are characterized by the abundance of the magnetic minerals as compared with the non-magnetic, and the bulk of this magnetic crop consists of tourmaline and iron-ores. In the case of the red sand, the actual proportions are 0.81 per cent. magnetic to 0.036 per cent. non-magnetic. The 'light' material is mainly

quartz, which in the case of the sands constitutes about 94·1 per cent. of the facies; associated with the quartz are kaolin, muscovite, glauconite, and authigenic matter, chiefly limonite in the yellow sands, and hematite in the red sands. In the clays the percentage of mica and kaolin is higher, though much of the material is an indeterminate 'paste,' probably consisting of quartz, sericite, chialstolite, rutile, and iron-ores; the mottling of these clays is due to variations in the degree of secondary oxidation undergone by the original iron-compounds.

DESCRIPTION OF THE MORE IMPORTANT MINERAL SPECIES.

Quartz.—This mineral occurs in subangular to well-rounded grains, usually coated with ferruginous cement. On clarification with acid, the grains are seen to be highly turbid, owing to inclusions of apatite, tourmaline, and rutile. No fluid cavities were noted in the grains.

Muscovite.—Varies considerably in composition. The 'light' material (S.G. < 2·82) presents fairly-clear irregular flakes of low polarizing character, usually showing good interference-figures. The denser facies which sinks in bromoform is turbid with inclusions of ferric oxide, tending to parallel arrangement within the flakes.

Magnetite is a noteworthy constituent of all facies of the deposit, and occurs in subangular grains; rounded octahedra are rare, though noted more in the red sands than in the other facies. In the clays, sharply angular fragments are seen (magnetite dust), of a brilliant silvery-grey colour by reflected light.

Ilmenite.—Owing to the absence of well-individualized magnetite, some little difficulty is experienced in differentiating ilmenite from that mineral; the abundance of leucoxene in the non-magnetic residue, however, is some measure of the proportion of original ilmenite, though in many cases rounded irregular grains of the species are clearly defined by their dull reddish-grey lustre in reflected light.

Tourmaline is exceedingly abundant, and in the yellow and red sands constitutes the greater part of the residue. It usually occurs as large, irregular, and rounded grains, of blue, green, brown, intermediate shades, and parti-coloured. The brown varieties show the strongest pleochroism, and many of the grains, being basal, exhibit uniaxial interference-figures. Besides the grains (though by no means so common), well-formed prisms are seen, generally striated, and having rhombohedral terminations and basal partings; doubly terminated varieties are rare. Such prisms are usually blue, green, or bluish-green, and are pleochroic: they have an average length of 0·3 mm., while the grains frequently measure 0·25 mm. along their greatest length.

Staurolite.—Only a few grains of indubitable staurolite were recognized, although the mineral may actually occur in greater proportion, or at least with more constancy than is to be inferred from the determinations made. The grains are well rounded, but characterized by their deep brownish-yellow colour, making distinction between them and the abundant brown tourmaline a difficult matter. The weaker pleochroism and higher refractive index than the tourmaline were noted; but the most reliable differentiating factor was the biaxial positive interference-figure revealed in some cases.

Leucoxene.—Abundant and occurring in dull whitish-grey pellets (as seen by incident light), well rounded, with occasionally a core of unaltered ilmenite. The grains have a rough and pitted appearance, and are frequently stained brown.

Zircon.—Two very distinct varieties of zircon occur, well-rounded doubly-terminated prisms averaging 0·3 mm. in length, and short, 'stumpy,' but well-defined prisms with irregular terminations. The former type is usually full of inclusions, and is more characteristic of the basal yellow sands; the latter variety is almost transparent with only occasional fluid (?) cavities, and is more typical of the red sands and clay. The scarcity of this mineral at the base of the series, its common occurrence at the middle horizons, and its gradual diminution in proportion as the upper beds are reached, considered together, are noteworthy features.

Kyanite.—These crystals are certainly distinctive, and occur as elongated prisms determined by the (100) cleavage and (001) parting: traces of a well-marked (010) cleavage are nearly always present; the grains have suffered much abrasion, and are on the whole extremely well rounded. They strongly resemble analogous grains found in the Lower Greensand. (Fig. 3, p. 371.)

Anatase.—Absent in the sands and occurring but rarely in the clay as indigo-blue tabular crystals perfectly formed. Probably secondary, derived from the decomposition of ilmenite.

Rutile.—This mineral is not so common as might be expected, and well-formed crystals are rare. Generally it occurs in well-rounded 'foxy' red grains, rudely prismatic, measuring 0·25 mm., and void of any pleochroism.

Topaz.—Well-rounded, clear, and transparent grains of topaz are characteristic of the red sands and clay, but less common in the yellow sand. The grains are variable in size, measuring from 0·1 to 0·2 mm. in diameter, but occasionally attaining 0·5 mm. They are easily distinguishable from the andalusite by their transparency, absence of pleochroism, and by the biaxial positive interference-figures exhibited by many of them.

Andalusite.—This mineral constitutes the most important, and at the same time the most interesting, feature of the St. Agnes deposits. It occurs both as irregular rounded grains and as well-formed prismatic crystals, and in most cases exhibits characteristic blood-red pleochroism, more intense and striking than in the case of any other known occurrence of the mineral in British sedimentary strata. The 'rounded grain' type, which is the commoner mode of occurrence, presents marked subconchoidal fractures, and is usually less turbid with inclusions than the crystals; the latter consist of well-formed rhombic prisms terminated by (011) faces or by the basal pinacoid; grains flattened parallel to (001) are normal to the acute bisectrix, and show biaxial negative interference-figures. The inclusions are mainly quartz, graphite, and magnetite, and in some cases secondary alteration-products are developed, the chief of which has been recognized as kaolin. The pleochroism and usually turbid character of the mineral serve to differentiate it easily from the associated topaz, to which it is only subordinate in quantity in the red-sand horizon.

Cassiterite.—This mineral is by no means common, and no trace of it was found in the red sand. In the basal sands and also in the clay, however, one or two dusky-brown, rounded, tetragonal crystals were observed, measuring about 0·2 mm. in length.

(b) St. Erth.

As stated previously (p. 353) six definite lithological horizons were recognized in the St. Erth sands, in the vertical section shown in the Cornish Sand Company's pit; but only the upper yellowish-brown sand was traceable laterally. The following table

shows the results of the microscopical examination of the various facies:—

	Horizon	A.	B.	C.	D.	E.	F.	G.
Light Material: S.G. < 2.82.	Minerals.	Essential and dominant constituent throughout.						
	Quartz	5	5	5	5	5	5	5
	Kaolin	6	6	4	4	4	5	4
	Muscovite	4	4	4	3	4	3	4
	Ferruginous cement.	Essential authigenous material throughout.						
Heavy Residue: Magnetic. S.G. > 2.82.	Magnetite	7	7	7	5	6	6	7
	Ilmenite	5	7	5	5	6	5	5
	Garnet	1	1	1	—	—	—	1
	Tourmaline	8	8	8	8	8	8	8
	Staurolite	5	5	4	2	4	4	4
	Epidote	4	4	4	4	4	4	4
	Chlorite	—	—	—	—	—	—	—
	Biotite	4	1	2	1	—	—	1
Heavy Residue: Non-Magnetic. S.G. > 2.82.	Leucoxene	7	7	7	5	8	6	7
	Zircon	9	9	9	5	4	8	9
	Kyanite	5	4	5	6	6	3	5
	Anatase	1	—	—	—	1	—	1
	Rutile	7	6	6	4	6	4	6
	Brookite	—	1	—	—	—	?	1
	Topaz	5	4	4	4	3	3	4
	Aandalusite	5	5	5	5	6	7	5
	Muscovite	5	5	4	4	4	4	4
	Corundum	—	—	—	—	—	—	—
	Cassiterite	4	4	?	—	—	—	4
	Xenotime	?	—	—	—	—	—	?

A. Yellowish-brown sand, 6 feet below the surface. Average of several samples taken laterally, including one from the Cornish Sand Company's pit.

B. White sand, 8 feet below the surface, Cornish Sand Company's pit.

C. Brown sand, 14 feet below the surface, Cornish Sand Company's pit.

D. Reddish-brown sand and grit, 20 feet below the surface, Cornish Sand Company's pit.

E. Chocolate moulding sand, 22 feet below the surface, Cornish Sand Company's pit.

F. Reddish-brown sand, 23 feet below the surface, bottom of the pit, Cornish Sand Company's pit.

G. Average composition of the St. Erth sands.

[Conventional signs as in the previous table, p. 357.]

A quantitative estimation of the mineralogical composition of an average sample of St. Erth sand gave the following results:—

Quartz, 91.6 per cent.

Authigenous and other 'light' material, 8.26 per cent.

Magnetic residue, 0.120 per cent.

Non-magnetic residue, 0.025 per cent.

From this it will be seen that the relative proportion of the magnetic to the non-magnetic residue is less, and the percentage of authigenous matter (chiefly limonite) greater than in the case of the St. Agnes deposits. The principal mineralogical features of the St. Erth sands consist in the abundance of tourmaline (variable in colour, size, and shape), in the marked 'flooding' of well-rounded zircon-crystals at the upper horizons, in the rare appearance of garnet (absent both at St. Agnes and St. Keverne), in the presence of staurolite in variable quantity throughout, and in the occurrence of the same type of kyanite (fig. 2, p. 371) as that remarked at St. Agnes, though generally less common here than at that locality. Quartz, muscovite, magnetite, ilmenite, kyanite, and cassiterite all present characteristics similar to the species occurring at St. Agnes (p. 358), and need not be further mentioned. The following minerals, however, are specially to be noted :—

Garnet.—This mineral, although very rare, is distributed laterally throughout the upper yellowish-brown sand, and also vertically through the upper facies of the deposits. It occurs as subangular grains never longer than 0·2 mm., with a refractive index of about 1·76, pink in colour, and traversed by numerous intersecting cracks. Its isotropic character is consistent.

Tourmaline.—This most abundant mineral is present both as large and as small grains and prisms, the prisms averaging about 0·3 mm. and the grains 0·25 mm. in length. The colours range from grey, blue, purple, green, brown, to yellow, and in many cases parti-coloured grains are seen. A noteworthy feature of the species is its occurrence as basal sections yielding good uniaxial interference-figures; such basal grains are extraordinarily common at all horizons, and are indistinguishable from similar grains noticed in the St. Agnes deposits (p. 358). Extreme rounding, subangularity, and irregular outline of grains are all developed, the last-mentioned feature being especially noticeable in the reddish-brown sand near the base of the series.

Staurolite.—Common in the upper beds, but scarcer at the lower horizons, this mineral is well individualized at St. Erth. It occurs as rounded brownish-yellow grains, exhibiting weak pleochroism, high refractive index and, in some instances, biaxial interference-figures. The average grains measure 0·2 mm.

Epidote.—Grains of this mineral, when present, are all very similar. They present sharply angular outlines, clear greenish-yellow coloration in transmitted white light, a refractive index equal to that of the garnets, and weak pleochroism. Between crossed nicols, third-order birefringence colours (chiefly blues and yellows) are exhibited, and many of the grains show typical partial interference-figures for cleavage-flakes parallel to (100).

Zircon.—Reference has already been made above to the 'flooding' of this mineral at certain horizons, which is its most characteristic feature. Compared with the other minerals associated with it, and also with the similar species occurring at St. Agnes, the St. Erth type is much smaller, and much more rounded; the average size is 0·1 mm.

Rutile.—In contrast to the St. Agnes deposits, this mineral occurs very commonly at St. Erth; the prevalent type of grain is a well-rounded, dusky reddish-brown prism, with faint pleochroism and a very high refractive index. Sharply angular and irregular fragments of clear yellow rutile also occur, especially in the uppermost yellowish-brown sands.

Brookite.—Only one grain of this mineral was identified in the samples examined, and this occurred in the white sand associated with rutile, as an irregular, well-rounded, yellow crystal flattened parallel to (100) and striated parallel to the vertical axis. The grain is feebly pleochroic, possesses a very high refractive index and birefringence, and exhibits a well-defined biaxial positive interference-figure.

Topaz.—This mineral is commoner in the upper horizons than in the lower, and in some cases occurs in excess of the andalusite. The grains are usually somewhat irregular, but are clear, colourless, void of inclusions, and average from 0·2 to 0·3 mm. in diameter.

Andalusite.—The chief feature of this species, as occurring here, is the intense blood-red pleochroism exhibited by nearly all the crystals, which are in this, and in all other respects, similar to those of St. Agnes.

(c) St. Keverne.

Microscopical examination of the Crousa-Common deposits gave the following results:—

	Horizon	A.	B.	C.	D.
Light Material: S.G. < 2·82.	Minerals.				
	Quartz	Essential constituent throughout.			
	Muscovite	5	5	5	5
	Glaucconite	3	2	3	2
	Ferruginous cement	Essential authigenous material.			
Heavy Residue: Magnetic. S.G. > 2·82.	Magnetite	7	7	7	7
	Ilmenite	8	8	8	8
	Garnet	—	—	—	—
	Tourmaline	8	8	8	8
	Staurolite	1	1	1	1
	Epidote	4	4	4	4
	Chlorite	1	1	1	1
	Biotite	2	1	1	1
Heavy Residue: Non-Magnetic. S.G. > 2·82.	Leucoxene	7	7	8	7
	Zircon	4	4	5	4
	Kyanite	—	—	—	—
	Anatase	5	5	8	5
	Rutile	4	4	5	4
	Brookite	—	—	2	2
	Topaz	4	5	5	5
	Andalusite	8	9	9	9
	Muscovite	5	5	7	5
	Corundum	—	—	—	—
	Cassiterite	4	4	1	4
	Xenotime	—	—	—	—

A. 'Gravel' from Crousa Common, St. Keverne. (Average of several samples.)

B. 'Gravel' from a quarry by the main road, 9th milestone from Helston, St. Keverne.

C. 'Gravel' from the base of the deposits, same locality as B.

D. Average composition of the St. Keverne deposits.

[Conventional signs as in the previous tables.]

The mixed, unsorted character of these Crousa-Common deposits renders quantitative data of little direct value in this case. Mention has already been made of the variation in grade-size shown by the constituent particles, and the general coarse texture of the sands has been commented upon; such variations are reflected in the elutriation-curve for these sediments plotted by Prof. P. G. H. Boswell, which compares very unfavourably with the curve of the St. Erth facies.¹ It would be expected that the coarser the sample is in the aggregate, the less will be the yield of heavy residue, and this was found to be the case in the present instance. The samples collected varied considerably in average texture, and the residues fluctuated quantitatively from 0.01 to 0.2 per cent. The only uniform feature was the mineralogical composition of the sediments, which was found to be constant qualitatively throughout. The characteristic minerals, both in frequency of occurrence and in optical properties, are undoubtedly ilmenite, anatase, and andalusite; the last-mentioned species particularly predominates in some samples, and in one non-magnetic residue, save for three grains of anatase, it constituted the entire crop. The negative characteristics that should be noted are the extreme rarity of staurolite, the entire absence of kyanite and garnet, and the dropping-off of zircon, when these minerals are considered with reference to the other deposits.

Ilmenite.—The contrast between this mineral and the magnetite tends to be most marked in these deposits; whereas the latter frequently occurs in well-recognizable octahedra, the former is invariably irregular, fragmental, and ragged. In some cases the partial alteration to leucoxene can be seen, and secondary outgrowths of tiny ultra-microscopic crystals (probably of rutile or anatase) from the opaque nucleus are by no means uncommon.

Tourmaline.—This species is again remarkable for the abundance of basal grains, as at St. Agnes and St. Erth. Prismatic crystals are present, but less frequently than at those localities. The prevalent type is usually rounded but subangular, and many grains show a marked fracturing. The average grain measures 0.4 mm. in diameter.

Anatase.—This species is undoubtedly the distinctive feature of these deposits, and in no other sediment known to me are the crystals so abundant, so beautifully formed and preserved, and so conspicuous as they are here. The common type is tabular parallel to (001), either as individual crystals or as composite groups of tabular forms in parallel growth. The colour is invariably indigo-blue or greyish-blue; refractive index extremely high; birefringence high, but tending to be masked by the natural colour; interference-figure (uniaxial negative) remarkably clear. These crystals average about 0.25 mm. in longest diameter. Occasionally fractured grains occur which are almost opaque in white light, but easily studied and identified with convergent light.

Andalusite.—On the whole, grains of this mineral assume much larger dimensions here than in former instances. They are rarely well crystallized, but tend to occur as rudely triangular fragments, fractured, with 'pitted' surfaces, and often crowded with inclusions. The blood-red pleochroism is

¹ 'British Resources of Sands & Rocks used in Glass-making' 2nd ed. (1918) pp. 30, 31.

shown by many individuals, but several of the grains are bereft of this property, particularly the clearer and more irregular types. The refractive index and birefringence are normal, and a few grains exhibit biaxial negative interference-figures. The average diameter of the grains is 0.5 mm., and frequently natural grading factors have produced local concentrates composed of individuals almost without exception conforming to this dimension. In both physical and optical characters, this andalusite differs in no fundamental respects from that found in the more northern localities.

The other minerals present call for no special remark, save possibly the brookite, of which two grains were identified in the samples taken from the base of the deposits. These grains exhibited characteristics similar to those possessed by the same mineral noted in the St. Erth Beds.

VI. COMPARISON AND CORRELATION OF THE DEPOSITS.

Average mineralogical composition.			
Species.	St. Agnes.	St. Erth.	St. Keverne.
Magnetite	7	7	7
Ilmenite	5	5	8
Garnet	—	1	—
Tourmaline	8	8	8
Staurolite	3	4	1
Epidote	4	4	4
Chlorite	2	—	1
Biotite	2	1	1
Leucoxene	7	7	7
Zircon	5	9	4
Kyanite	6	5	—
Anatase	2	1	5
Rutile	2	6	4
Brookite	—	1	2
Topaz	5	4	5
Andalusite	7	5	9
Muscovite	5	4	5
Corundum	?	—	—
Cassiterite	1	4	4
Xenotime	? 1	?	—

[Conventional signs as in the previous tables.]

If we compare the average mineralogical composition (heavy residues) of the St. Agnes, St. Erth, and St. Keverne deposits, taking also into account the crystallographical, physical, and optical properties of the component species, it soon becomes abundantly clear that, although we are dealing with isolated outcrops, the deposits all present marked petrographical affinities suggesting a close genetical relationship. Reviewing the results of the investigation from the purely mineralogical standpoint, and in order to validate subsequent questions of correlation and source of origin of material, we have to enquire into the cumulative evidence furnished by the more important mineral species, especially with regard to their frequency or infrequency of occurrence, their persistence in each locality, and the constancy of their mineralogical properties as an indication of consanguinity of origin.

(i) Frequency of Occurrence (deduced from the average mineralogical composition of each deposit).

Abundant.	Magnetite, tourmaline, leucoxene, andalusite.
Common.	Ilmenite, zircon, topaz, muscovite, kyanite.
Scarce.	Epidote, rutile, cassiterite, staurolite, anatase.
Rare.	Garnet, chlorite, biotite, brookite.
Doubtful.	Corundum, xenotime.

(ii) Persistence of Species: (Distribution Diagram).

Mineral.	St Agnes.	St. Erth.	St. Keverne.
Magnetite	_____	_____	_____
Ilmenite	_____	_____	_____
Garnet	_____	_____	_____
Tourmaline	_____	_____	_____
Staurolite	_____	_____	_____
Epidote	_____	_____	_____
Chlorite	_____	_____	_____
Biotite	_____	_____	_____
Leucoxene	_____	_____	_____
Zircon	_____	_____	_____
Kyanite	_____	_____	_____
Anatase	_____	_____	_____
Rutile	_____	_____	_____
Brookite	_____	_____	_____
Topaz	_____	_____	_____
Andalusite	_____	_____	_____
Muscovite	_____	_____	_____
Corundum	?	_____	_____
Cassiterite	_____	_____	_____
Xenotime	?	_____	_____

(iii) Constant Mineralogical Features noted throughout.

Magnetite.	Rounded octahedra or grains. Not ragged.
Ilmenite.	Commonly irregular and ragged.
Tourmaline.	Prismatic and rounded grains both present. Deep-brown basal sections with interference-figures very common. Numerous and parti-coloured grains occur in all cases.
Staurolite.	Well-worn grains with similar physical and optical properties noted throughout.
Epidote.	Always sharply angular, greenish-yellow in colour, many grains exhibiting partial interference-figures. Weak but characteristic pleochroism.
Zircon.	Extremely well-rounded prismatic forms characteristic in all cases. A few of the 'stumpy' prismatic varieties always present.
Kyanite.	Precisely the same type present in both the St. Agnes and the St. Erth deposits. The rounded, elongated prisms, showing traces of a well-marked (010) cleavage, are always present.
Anatase.	Commonly in indigo-blue tabular crystals, seldom abraded.
Rutile.	Well-rounded 'foxy'-red or reddish-brown, feebly-pleochroic grains are the prevalent type, with a subordinate amount of yellow translucent fragments.

- Topaz. Invariably clear, colourless and transparent, and in irregular flakes.
- Andalusite. Well individualized as regards optical properties, particularly that of pleochroism, which is intense in many grains. Often well crystallized, although usually turbid with alteration-products such as kaolin; contrasting strongly with topaz in these respects.

The foregoing species have been selected on account of their importance quantitatively, and on account of their value for purposes of correlation.

The marked similarity of the mineralogical composition of the sediments and of the more precise physical and optical characters of the component species, can only be explained on the assumption of derivation from a homogeneous 'distributive province,' using the phrase to include both igneous and sedimentary facies.¹ Quite apart from general lithological resemblance and similar mode of occurrence of the deposits, we find that (excepting two doubtful minerals), in only four cases are species non-persistent throughout, and of these all save one (kyanite) are comparatively unimportant. Such uniformity in composition is most significant, and is particularly striking in the present case. Again, the frequency of occurrence of the important species, and the similarity of crystallographical and optical properties, and of the nature and degree of abrasion exhibited by these species, are factors which we cannot overlook, and are strongly suggestive of the truth of the hypothesis above postulated. It would seem not unreasonable, then, to conclude that the deposits were the product of a definite period of erosion, subsequent denudation, probably marine, determining the removal of much of the detritus which had accumulated; the survival of a few isolated remnants of the original mass was by no means fortuitous, but due entirely to favourable conditions of deposition. On this basis, the initial assumption of contemporaneity of the deposits under discussion becomes a distinct probability, and receives support not only from the mineralogical evidence cited above, but also from topographical criteria to be discussed in the sequel.

VII. SOURCE OF ORIGIN OF THE DEPOSITS.

Any well-differentiated phase of detrital deposition must of necessity give rise to sediments reflecting the nature and composition of the parent rocks of the comminuted material; it follows, therefore, that an enquiry into the normal petrological habitat of the several mineral species concerned should furnish us with valuable evidence as to the source of origin of the deposits, which, when combined with the geological and physiographical knowledge obtainable from the area to-day, should serve as a foundation for a geographical reconstruction of this part of Britain at the epoch under consideration. The results of such an enquiry show that

¹ The term 'distributive province' was suggested by Mr. A. Brammall, M.Sc.

with the exception of two or possibly three of the mineral species characterizing these deposits, all occur in rocks known to-day in the vicinity of the outcrops under consideration: in other words, 85 per cent. of the species are probably of local origin. With regard to xenotime, this mineral has not been recorded from the acid igneous rocks of Cornwall, so far as I am aware; but there is no reason why it should not be present in some of the granite-masses, even though sparsely distributed. Staurolite is essentially an 'Armorican' mineral, with a type-locality in Brittany to-day: its origin may be more pertinently discussed hereafter (p. 370). The kyanite is probably in the nature of a remanié mineral, and its crystallographic features point to derivation from a pre-existing sediment, such as the Lower Greensand: the nearest outcrop of the Lower Greensand, containing kyanite similar to that of St. Agnes and St. Erth, is in the north-west of Wiltshire: the significance of this fact will be ultimately apparent.

The cumulative evidence to be obtained from a study of these minerals shows them to have belonged originally to a distributive province which included acid, basic, and ultrabasic rock-types, with an associated suite of metamorphic rocks: such a province clearly is only indicative of Cornwall itself where all such rock-facies are known to occur. Excluding, then, the staurolite and kyanite, the origin of which is discussed hereafter, the mainly local derivation of the deposits under investigation would seem to be most decidedly indicated.

VIII. PLIOCENE GEOGRAPHY OF THE SOUTH-WEST OF ENGLAND.

One of the most difficult problems facing the geologist in Western Cornwall is the adequate explanation of certain outstanding physical features, for which there is but little direct geological evidence; among such features that of the St. Erth valley (see map, fig. 1, p. 350) is probably the most striking, and a close investigation of its nature and origin is a *sine quâ non* in any intelligent discussion of Pliocene palæogeography.

The late Clement Reid, in a paper 'On the Probable Occurrence of an Eocene Outlier off the Cornish Coast,'¹ drew attention to this valley, and interpreted its origin in the light of his theory of the existence of Eocene gravels on the floor of Mounts Bay. He inclined to the view that the St. Erth valley was the site of an old Eocene river flowing probably from north to south through this valley, the river being responsible for the transportation and accumulation of the material in the bay. Thence the inference is that the initiation of this valley was the product of early Eocene erosion, the material, composed of 86 per cent. of Chalk flint and 2 per cent. of Greensand chert, being derived from Cretaceous rocks, presumably from the north-east. That the valley was not originally formed in Pliocene times is apparent from careful

¹ Q. J. G. S. vol. lx (1904) p. 113.

observation to-day; the mode of occurrence and the elevation of the St. Erth deposits at 170 feet above sea-level both tend to suggest a greater antiquity, and hence a probable Eocene age. On this assumption, the belief is justified that the whole of South-Western Cornwall, if not the greater part of the South-West of England, stood then at a higher level than it does now, and the forces of denudation probably continued to act unchecked throughout Oligocene and early Miocene times, and possibly later. Such a belief can only be based on analogy with contiguous areas to the east, since in Cornwall itself we have really no direct evidence of the trend of geological events between Upper Palæozoic and Pliocene times—an enormous gap in the stratigraphical record.

With the renewal of folding along the ancient Armorican lines in Miocene times, the effects of which are so marked in the Isle of Wight and the Isle of Purbeck, it is possible that considerable changes were wrought in the surface-relief of Southern Cornwall, although it is by no means certain that these tectonic influences extended so far westwards; if they did, it would be expected that the tendency was towards the production of asymmetrical fold-features with a gentler dip southwards, as is the case in these localities, though of far less severity in the west where the movements were decreasing in intensity. In Cornwall the effect of such deformation would probably only be an accentuation of the chief Palæogene physical features, and such drainage-courses as the St. Erth valley with its southerly gradient would receive an increased impetus in the work of discharging material into the English Channel. Even if the original early Tertiary drainage of the St. Erth valley were in the opposite direction: that is, from south to north (which is extremely unlikely from all that we can gather of its history), the result of Miocene earth-movement would still tend to produce drainage into the English Channel in South-Western Cornwall, and at the close of Miocene times the St. Erth valley would in any case be well differentiated. Whatever happened during this pre-Pliocene period, two factors stand out very clearly from the late Miocene records: namely, the general subsidence of the area in early Pliocene times and the concomitant accentuation of the '400-foot platform' as a result of marine erosion.¹ This Pliocene platform is one of the most characteristic physical features of Cornwall, and it can be traced at heights varying from 370 to 420 feet above O.D., at intervals along both the southern and the northern coasts of the county, extending from the coastal margin well inland to the higher Palæozoic country which constituted the ancient Pliocene land-area (shown in the accompanying sketch-map, fig. 1, p. 350). It is difficult to estimate the precise amount of this subsidence from the data at present available; but, taking into account the St. Erth deposits, the character of their fauna, their lithology, and present topographical evidence, Clement

¹ See Mem. Geol. Surv. Sheets 351, 358, 346, 359, and H. Dewey, Q. J. G. S. vol. lxxii (1916-17) p. 63.

Reid's estimate of 340 feet is probably under rather than over the actual amount, particularly when the St. Agnes and St. Keverne deposits are also considered.¹ The difference in topographic level of the St. Erth deposits compared with those of the other localities can only be due to the former having been laid down in a pre-existing hollow which, as subsidence progressed, became ultimately modified by the sculpturing of the '400-foot' feature: this implies deposition of the St. Erth material in deeper water than in the case of the other deposits, a belief justified both on palæontological and on petrographical grounds, and by comparison with the markedly shallow-water character of the St. Agnes and especially the St. Keverne facies. Thus the St. Erth valley, from its initiation as an early Tertiary river-course, became transformed at the close of Miocene times into a strait separating the Land's End area from that of the main Cornish land-mass; and it is noteworthy that, even with the present configuration of the land, a subsidence of only about 150 feet would be required to re-establish such conditions. With a subsidence of 364 feet, as above postulated, the geography of Western Cornwall assumes widely different aspects, the peninsula becoming in fact a series of large and small islands, a miniature West Indies.

Under such conditions of submergence the present nature and disposition of the Pliocene sediments is readily understood: at St. Agnes, the Beacon, rising to a height of 628 feet, becomes part of a large island, the northern and leeward shoreline of which formed the upper limit of the submarine shelf upon which the deposits were laid down. In the vicinity of St. Erth and Lelant, much larger islands existed on the west and on the east, the former comprising the Land's End granite and metamorphic area, the latter comprising the petrographically similar uplands of Carn Brea, Carn Menellis, and the Godolphin Hills. At St. Keverne, the Carn-Menellis mass is again the dominant background feature, and the gently sloping Lizard platform on the south becomes the locus of deposition of a mass of sand and gravel thence derived, a remnant of which has survived late Tertiary erosion and is preserved in the form of the present outcrop on Crousa Common. Then, as regards the Polcrebo deposits, in my opinion their occurrence at a height of 480 feet above O.D. can only with extreme difficulty be reconciled to this phase of geological history: if, in the absence of all other evidence, they are to be regarded as having been formed collaterally with the Pliocene deposits, how can we explain their present anomalous position above sea-level, and the absence of any like feature, either lithological or topographical, elsewhere in the county? Their general character would seem to fit in far more reasonably with Quaternary erosion than with any older period of denudation.

Hence, reviewing the chief features of these deposits of South-Western Cornwall in the light of the foregoing topographical data,

¹ 'The Pliocene Deposits of Britain' Mem. Geol. Surv. 1890, p. 65.

it is not difficult to understand the similarity of composition of their constituent minerals, their predominantly local derivation, the physical features of the grains (particularly quartz) as connoting the abrasive action of sea-water, and the indication of the deeper-water character of the St. Erth facies when compared with that of the other localities.

Lastly, the sources of origin of both the staurolite and the kyanite as 'foreign' minerals, and their bearing on the wider problem here discussed, have to be considered. In the case of the staurolite, the most probable source of derivation would seem to be from the south, from a land-mass, though now submerged, having geological and tectonic connexion with Brittany and the North-West of France, where we know this mineral to occur in quantity. The researches of Dr. H. H. Thomas¹ have shown that the staurolite in the Bunter deposits of Devon and Somerset probably had this origin, in view of the fact that the Armorican massif is generally considered to have extended much farther north-westward at the close of Upper Palæozoic times; although it was afterwards largely submerged, particularly in the late Cretaceous Period, renewed folding and uplift in Miocene times, involving the South of England and the North-West of France, determined the reappearance of this Armorican continent in the area now occupied by the English Channel, and the concomitant westward recession of the sea. The effect of this uplift would be to promote drainage both from Southern England and from the Armorican continent into a broad central river flowing westwards along the basin of the English Channel, and probably emptying itself into the sea at a point some miles south of the present Cornish coast. The action of marine currents bordering the western shore-line of this uplifted area would tend to the lateral distribution of the detritus brought down, although with a strong inclination to a northerly direction, owing to the probable south-westerly on-shore wind prevailing from the open ocean, as is the case at the present time. The comparative rarity of staurolite in the deposits, however, suggests a gradual alteration in potency and direction of these marine currents, such as would be occasioned by subsidence of the land-areas and the advance of the sea eastwards up the Channel once more; such factors reflect the initial conditions caused by the early Pliocene submergence to which reference has already been made.

In the case of kyanite, the evidence is much more obscure, though derivation from the north-east is suggested on petrographical grounds. Attention has already been called to the marked similarity between the Pliocene kyanites and those commonly occurring in the Lower Greensand; in order to test this point further, it became advisable to examine the non-magnetic residues from the Lower Greensand in the vicinity of Seend (Wiltshire), some 4 miles west of Devizes. Accordingly, such an investigation

¹ Q. J. G. S. vol. lviii (1902) p. 630.

was made, and with entirely satisfactory results. In figs. 2-4 from drawings of species occurring in St. Erth, St. Agnes, and North-Western Wiltshire, it will be seen that there is a marked similarity in crystal form in all cases; this is supplemented by a careful comparison of all the kyanite-grains in the Seend residue with those in the Cornish deposits. On the whole, the Pliocene grains are more worn and rounded than those of the Lower Greensand, as we should expect; but the species from Seend show the

Fig. 2.—*Kyanite from Pliocene, St. Erth* ($\times 70$).

Fig. 3.—*Kyanite from Pliocene, St. Agnes* ($\times 70$).

Fig. 4.—*Kyanite from Aptian, Seend, Wiltshire* ($\times 70$).

same characteristic prisms terminated by (001) or basal parting, further individualized by cleavage-traces parallel to (010) and (001), as well as the short 'stumpy' varieties met with in the Pliocene deposits. This mineralogical similarity seems, at first, to be but slender evidence on which to found a source of origin for the kyanite occurring in the Cornish deposits; but, when certain other factors are taken into account, it soon becomes apparent that this north-eastern region was indeed the most probable source of supply.

The evidence of the existence of an ancient Eocene drainage from north to south has already been mentioned; as a matter of fact, the occurrence of scattered Chalk flints is by no means uncommon in Cornwall, as, for example, at Newquay¹ and Padstow,² where in the latter locality it is associated with Greensand chert as at Ludgvan,³ the area examined by Clement Reid. The significance of this association of chert and flint is too strong to be ignored; clearly it suggests derivation from the east or north-east, where the typical developments of Cretaceous strata are known to occur. If we bear in mind the probably greater westward extent of such strata prior to early Tertiary erosion, it would seem not unreasonable to conclude that this material was carried south-westwards by an ancient river-system draining approximately along the line of the present Bristol Channel, receiving affluents possibly from South Wales on its northern bank and from Exmoor Forest and the northern part of Dartmoor on its southern bank, and finally emptying itself into the English Channel by way of the St. Erth valley. Such a drainage would be quite compatible with the little knowledge that we possess of the physiography of the South-West of England in the Palaeogene epoch, before the renewal of folding in Miocene times. There is little evidence to show that this folding entirely obliterated any western drainage previously existing; on the contrary, such a trend was accentuated rather than opposed, for a north-and-south watershed was probably well established west of the Cotswold Hills in early Tertiary times, differentiating a main east-and-west drainage, the former into the Thames basin, the latter into the Bristol-Channel and Exmoor region, although the precise location of this watershed is at present obscure in so far as our information goes.⁴ Miocene folding merely cut short the southward extension of that watershed by the superposition of an east-and-west line of flexures, now indicated by such tectonic features as the Kingsclere, Pewsey, and Mendip uplifts. Consequently, the ancestral drainage of rivers draining westwards, far from being obliterated, was resculptured to form the basis of the present river-system in this region, and material continued to be borne westwards until the Pliocene submergence set in. With this submergence came the gradual advance of the sea over the Miocene land-areas of the South-West of England, the drowning of pre-existing lowland topography, and the limitation of the distributive power of the sediment-bearing rivers. If the apportionment of the kyanite-grains in the Pliocene deposits is any criterion of these fundamental physiographical changes, then we can readily appreciate the absence of the species at St. Keverne,

¹ Mem. Geol. Surv. Sheet 346 (1906) p. 65.

² *Ibid.* Sheets 335 & 336 (1910) p. 93.

³ *Ibid.* Sheets 351 & 358 (1907) p. 68.

⁴ Some light was thrown on this problem recently by Mr. W. D. Varney at a meeting of the Geologists' Association on May 6th, 1921, when a paper on the 'Geological History of the Pewsey Vale' was read (Proc. Geol. Assoc. vol. xxxii, p. 189).

its appearance at St. Erth, and its still commoner occurrence at St. Agnes, St. Keverne being the southernmost and St. Agnes the northernmost locality. The probable trend of advance of the Pliocene sea was from south-west to north-east, and obviously as this sea deepened, a constantly diminishing amount of material would find its way from the north-east to the submerged parts of Cornwall, and the influence of the drainage would be progressively curtailed. Again, the occurrence of staurolite at St. Agnes would seem to suggest the influence of south-westerly marine currents at least as far north as that locality, which further explains the absence of kyanite in the extreme south.

Finally, the possibility of derivation of the kyanite from any pre-existing Eocene deposits in South-Western Cornwall is negatived by the entire absence of Chalk flints and Greensand cherts from the Pliocene deposits, indicating the extensive erosion that the older deposits suffered in early and Middle Tertiary times.

IX. SUMMARY AND CONCLUSIONS.

The results of the investigation may now be summarized as follows:—

(1) The petrographical characters of the St. Agnes, St. Erth, and St. Keverne deposits have been shown to be substantially the same, and they suggest derivation from rocks belonging to a homogeneous 'distributive province' such as would be furnished by the Palæozoic rocks of Cornwall.

(2) The geological age of the St. Erth Beds has previously been proved palæontologically to be early Pliocene. Although no fossils occur in the St. Agnes or St. Keverne deposits, and since the latter are the products of contemporaneous erosion, by petrographical correlation their Pliocene age is established.

(3) In the case of the alleged occurrences of Pliocene material at Canons Town and Polcrebo, in neither instance is the evidence sufficient to establish relationship with the other deposits, although there is little doubt that, if an outcrop exists at the former locality, it has a direct connexion with the St. Erth material on the opposite side of the valley. The Polcrebo gravels are, in my opinion, the product of much later erosion.

(4) The topographical evidence furnished by the '400-foot' plateau has been used, in conjunction with the petrographical investigation of the deposits associated with it, as a means of reconstructing the early Pliocene geography of Cornwall. The occurrence and distribution of the two species, staurolite and kyanite, have been shown to be of specific value in this connexion, the former as connoting the existence of the ancient Armorican land-mass, the latter as indicating the direction of drainage from the north-east, at the close of Miocene and the commencement of Pliocene times.

In conclusion, it is hoped that the methods employed and the results obtained from this investigation will indicate a possible solution in other cases where palaeontological evidence is scanty or wanting: used cautiously and over limited areas, such petrographic methods should prove invaluable to the stratigrapher.

It remains for me to record my thanks to Prof. W. W. Watts, Dr. H. H. Thomas, and Prof. P. G. H. Boswell for their kind help during the course of this work. Mr. G. M. Part very kindly reproduced the kyanite-grains shown in figs. 2-4, and I am also indebted to Mr. G. S. Sweeting for the assistance which he has rendered during the preparation of the manuscript.

DISCUSSION.

Prof. P. G. H. BOSWELL welcomed the paper as a contribution to our knowledge of the petrology of the Tertiary deposits of the West of England. The Author's records of the characteristic minerals were confirmed by the speaker's own identifications. It was a noteworthy but unexplained fact that, while the Permian, Trias, Lias, and Inferior Oolite of the West of England were characterized by an abundance of garnet, that mineral was absent from, or extremely rare in, the Cretaceous, Eocene, Oligocene, and Pliocene of Devon and Cornwall, although it was a common constituent of the Palaeozoic rocks of Devon, Cornwall, and Brittany.

He enquired why the Author desired to have the staurolite in the St. Keverne sands derived from the old 'Armorican' land on the south-west, unaccompanied by its usual associate, kyanite; while, in the case of the sands at St. Agnes and St. Erth, he assumed a Lower Greensand origin in the north-east for the same two minerals. The absence of kyanite at St. Keverne seemed to be inconclusive in the matter of the derivation of the material.

The paper was valuable for the additional light which it threw upon early Pliocene geography. The Author's conclusions, although novel, were not necessarily inconsistent with our ideas of the distribution of Pliocene land obtained from a study of the fauna of the St. Erth clays and the Craggs. That the migration of southern species into the North-Sea basin over what is now the English Channel and Kent was possible in early Pliocene times, but was prevented during the deposition of the Middle and Upper Pliocene, presumably by the raising of a land or shallow-water barrier, is indicated by the molluscan faunas. Further, the totally different character of the mineral assemblages of the Cornish and East Anglian Pliocene (the latter having apparently been derived from the south-east) supports the view. Moreover, the similarity in certain mineralogical respects (notably in the rarity of garnets) of the Lenham Beds and the Cornish Pliocene may prove to be more than mere coincidence.

Mr. G. M. PART said that he had hoped that this paper might suggest some reasonable source for the very similar assemblage of minerals found in some of the Glacial drifts of Pembrokeshire, which it could only be surmised were derived from some similar Tertiary deposit. As the Pembrokeshire drifts were derived from a westerly or north-westerly direction, this would involve a northern drainage, if Cornwall had provided any of the material for a deposit from which the blood-red pleochroic andalusite had found its way into the gravels.

Dr. H. H. THOMAS agreed with the Author that the kyanite of these deposits was most probably derived from sediments of Cretaceous age. The absence of kyanite from the Western New Red rocks was strong evidence in support of the Author's view. He thought that the grains of staurolite with frayed-out cleavages owed this distinctive character to their derivation from large crystals: that was the conclusion to which he had come from a study of the abundant and large grains found in the Western Trias. With regard to the great similarity between the mineral assemblages of the Cornish Pliocene and the drift-sands of Pembrokeshire, he had many years ago suggested the latter's partial derivation from Tertiary deposits occupying, in Glacial times, a position in the bed of the Irish Sea.

Mr. G. BARROW was greatly interested in the Author's work, as it dealt with what are commonly known as Pliocene deposits, now occurring at heights much above sea-level. The Geologists' Association had taken a special interest in these high-level deposits, which occurred in patches extending from the south-east of Kent at least as far as the neighbourhood of the Guildford gap in the Chalk. Apart from the Lenham Beds, fragments of undoubtedly marine shells have been found in the gravels of Headley Heath. The mode of occurrence of these is important, as it suggests where to look for further casts. They occur only when the sand surrounding the original shell-fragments has been firmly cemented by iron-oxide, and nowhere else. The examination of the deposit on the ground suggests that these gravels are beach-deposits, with broken shell-fragments once common in them. All these fragments have been dissolved; but, where iron-oxide filtered in and cemented the sand before solution took place, casts of some fragments are preserved. It is in such cemented patches that we must in future look for evidence of the age and nature of these beds; this knowledge not only shows where to look, but where it is useless to look, and this so far covers more than 90 per cent. of the whole.

Mr. T. CROOK said that it was particularly pleasing to note the emphasis laid on sampling. Failure to record a mineral in such deposits did not necessarily mean that the mineral was absent; but, with careful sampling, such as the Author appeared to have carried out, much better results were likely to be obtained than when records were made on specimens collected haphazard. It

seemed to the speaker that it would be very useful if the Author would include in his paper an account of the method of sampling adopted, so that other workers might be able to obtain results that were fairly comparative.

With regard to the mineral composition of the sediments described, it was perhaps worth while to enquire whether the relative amounts of such minerals as garnet, staurolite, and kyanite, which were all metamorphic minerals in the ordinary sense, and might have emanated from the same ultimate source, were in any way connected with differences in chemical stability. Such differences had a good chance of asserting themselves where the proximate derivation was from other sediments, and where consequently the minerals had suffered repeatedly from the action of processes incidental to detrital sedimentation, possibly under a wide range of climatic variation.

Dr. J. W. EVANS thought it improbable that the relative level of land and sea changed to the same extent throughout the area concerned. He did not believe that material could have been transported from the north-east by coastal wave-action. On the northern coast of Devon and Cornwall it was the north-westerly winds that produced the most important transporting action, and the movement was from south-west to north-east, not *vice versa*. If the kyanite had travelled from the Lower Greensand of the neighbourhood of Devizes, it must have been by means of river-action, when the Bristol Channel was a tract of alluvium and Devon and Cornwall were at a relatively low level.

Mr. R. B. NEWTON declined on palæontological grounds to accept a Pliocene age for the St. Erth deposits. His own studies (see Journ. Conch. vol. xv, 1916) of the shells from those beds were all in favour of their Upper Miocene horizon, and as exactly the same facies was apparent among the Lenham mollusca, he was of opinion that the St. Erth and Lenham Beds were of contemporaneous origin. He mentioned the occurrence of similar species of shells in the Gourbesville deposits of Normandy which had been described by M. Gustave Dollfus (Bull. Soc. Géol. Normandie, 1880, and C. R. Assoc. Franç. Av. Sci., Cherbourg, 1906, pp. 358-70), and referred to the Redonian stage of the Miocene, which is considered the equivalent of the Upper Vindobonian horizon of Europe. The speaker was also of opinion that the palæontological evidence proved that the St. Erth as well as the Lenham deposits represented fragmentary remnants of the Continental Miocene development, which extended from Holland, Denmark, Northern Germany, and Northern France.

The AUTHOR, in reply to Prof. Boswell, said that it appeared to him unlikely that the staurolite could have come from the north-east, in view of the absence of kyanite from St. Keverne; if both the minerals had been derived from the north-east, kyanite should have penetrated at least as far as the staurolite, and it should appear with the latter at St. Keverne, which is actually not the

case. In reply to Mr. Part, the Author said that he had noticed the resemblance of the andalusite from the Glacial gravels of Pembrokeshire to the Pliocene species, but there was little doubt in his mind that the source of the Pembrokeshire deposits was from the west, possibly from an area now covered by the Irish Sea. In answer to Mr. Crook, the Author discussed the methods of sampling in the field at equal intervals along the strike of the deposits, and at each change of the lithological facies in vertical sections. The Author agreed with Dr. Evans that probably Cornwall stood at a higher level in early Tertiary times than it does at present; he specially drew attention, however, to the distinction necessary between the Tertiary deposits now occurring on either side of Dartmoor. In reply to Mr. Newton's criticism of the use of the word 'Pliocene' in connexion with these deposits, the Author said that this was essentially a palæontological aspect of the subject, and one which he did not feel competent to discuss; he had always been content to accept as a basis the admirable work of the late Mr. Clement Reid on the Pliocene Deposits of Britain.