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KAOLINIZED DEVONIAN METASEDIMENTS ADJACENT TO THE ST AUSTELL GRANITE CORNWALL

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Large volumes of kaolinized Devonian metasediments, similar in size to the larger kaolin bodies within the St Austell granite, are described from the Indian Queens area on the south side of Goss Moor, Cornwall. The area of kaolinization is within the metamorphic aureole of the granite. It was exposed in excavations from the recently constructed A30/A39 interchange, and has been encountered in boreholes and trenching in the area between Indian Queens, Gaverigan and Wheal Remfry china clay pit. Features within the kaolinized metasediments include calcium silicate rocks, minor acid intrusions, tourmalinization and tourmalinite breccia, a sheeted vein system, and cross-course Fe/Mn mineralization. It is likely that a granite ridge with only shallow cover extends northwards from Wheal Remfry china clay pit. A comparison of the nature of the kaolinite with Eocene/Oligocene weathering mantle, and kaolinite from earlier Mesozoic weathering profiles, indicates that the kaolinization at Indian Queens belongs to the earlier event; and it is suggested that, following an initial hydrothermal phase, intense kaolinization occurred on the downward limb of a fresh water convection cell. The preservation of the deep kaolinization at Gaverigan may be a consequence of an easterly downthrowing fault in the Cenozoic which might also have created the depression at Goss Moor.

The kaolinized metasediments are fine grained, the mineralogy being dominated by structurally well-ordered kaolinite and very fine quartz. The chemistry shows similarities with ball clays, but the physical properties are more akin to those associated with china clay from kaolinized granite, except that the brightness is low. Kaolin from metasediments has limited potential for some ceramic and other uses, but not for paper.

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INTRODUCTION

The St Austell granite is the most intensely kaolinized of the Cornubian granites, and most of the kaolinization occurs in the western, younger part of the granite. Earlier studies (Exley, 1959 and Bristow, 1968) tended to assume that the kaolinization was restricted to the granite, but field evidence accumulated in recent years has demonstrated that Devonian rocks have been intensely kaolinized in places, sometimes at locations a long way from the nearest granite. One of the most extensive areas of kaolinization outside the granites lies in the area between Indian Queens and Goss Moor (Figure 1). Here, metasediments of presumed Lower Devonian age, within the metamorphic aureole of the St Austell granite, have been extensively altered to form a kaolinized body comparable in size to kaolinized zones within the granite.

One of the earliest indications of this kaolinization was in Indian Queens cemetery [SW 921 592], Figure 1, where, when a grave was dug, white kaolinized material was encountered. In the early 1970s, ECC carried out gravity geophysical studies on the north side of the St Austell granite and discovered a large gravity low to the east of Indian Queens. One interpretation was that this might be a massive body of kaolinized granite under a thin cover of metasediments, so a borehole was drilled in the centre of the gravity low, at Gaverigan. This found 60 m of kaolinized metasediment overlying unkaolinized metasediment, which extended to a considerable depth, granite not being encountered until 294 m. As the granite was not kaolinized to any appreciable extent, it was concluded that the gravity low was primarily caused by, a deep Rocket of kaolinized metasediments.

Some years later, a metal mining company negotiated-exploration rights over this same area and carried out a systematic programme of geochemical testing, trenching and drilling for tin. The intensity of argillic alteration was noted on the-core logs, and argillic alteration was found to be pervasive and in some cases was recorded to considerable depths. The approximate extent of argillic alteration in each borehole is indicated in Figure 1, but as many of the boreholes were inclined, these figures should be treated as only an indication. Camm and Dominy (1997) discuss the tin mineralisation in the Indian Queens area using this borehole data.

Construction of the Indian Queens bypass in 1993 involved deep excavations for the two bridges at the A30/A39 Highgate Interchange. This exposed the kaolinized metasediment as well as some kaolinized acid igneous rocks. The excavations enabled samples to be taken to examine the mineralogy, chemistry and technical properties, which along with the geology, are described here.

GEOLOGY

Wheal Remfry china clay pit is within a lobe of granite which appears to form a ridge orientated north-south (Figure 1). The contact between the granite and adjoining metasediments is visible in the pit (Bristow and Howe, 1995). It is quite irregular in the north-east corner and a sub-horizontal sill of weakly kaolinized granite occurs (no longer visible). There is some faulting in this area, although the actual contact does not appear to be faulted. Some narrow zones of kaolinization in the aureole metasediments, which visually resemble the Highgate Interchange material, are present in this part of the pit. On the west side, the granite and metasediments in the vicinity of the contact are intensely greisened and the material is hard enough to have been quarried to provide sub-base material for road construction. The northern part. of Wheal Remfry pit is in a distinctive pink microgranite along with tourmalinite breccia. The contact relationships between microgranite and breccia are intrusive, with fluidal wisps of the granite interbanded with breccia, indicating both were fluid at the same time. As the breccia has been $^{40}Ar/^{39}Ar$ dated at 270 Ma (Chesley *et al., 1993),* It suggests that the, coeval microgranite is likely to be a similar age. Further north, at Castle- an-Dinas, a younger granite phase was dated by Darbyshire and Shepherd (1994) at 268 Ma. Thus, it would appear that one of the granite phases at the western

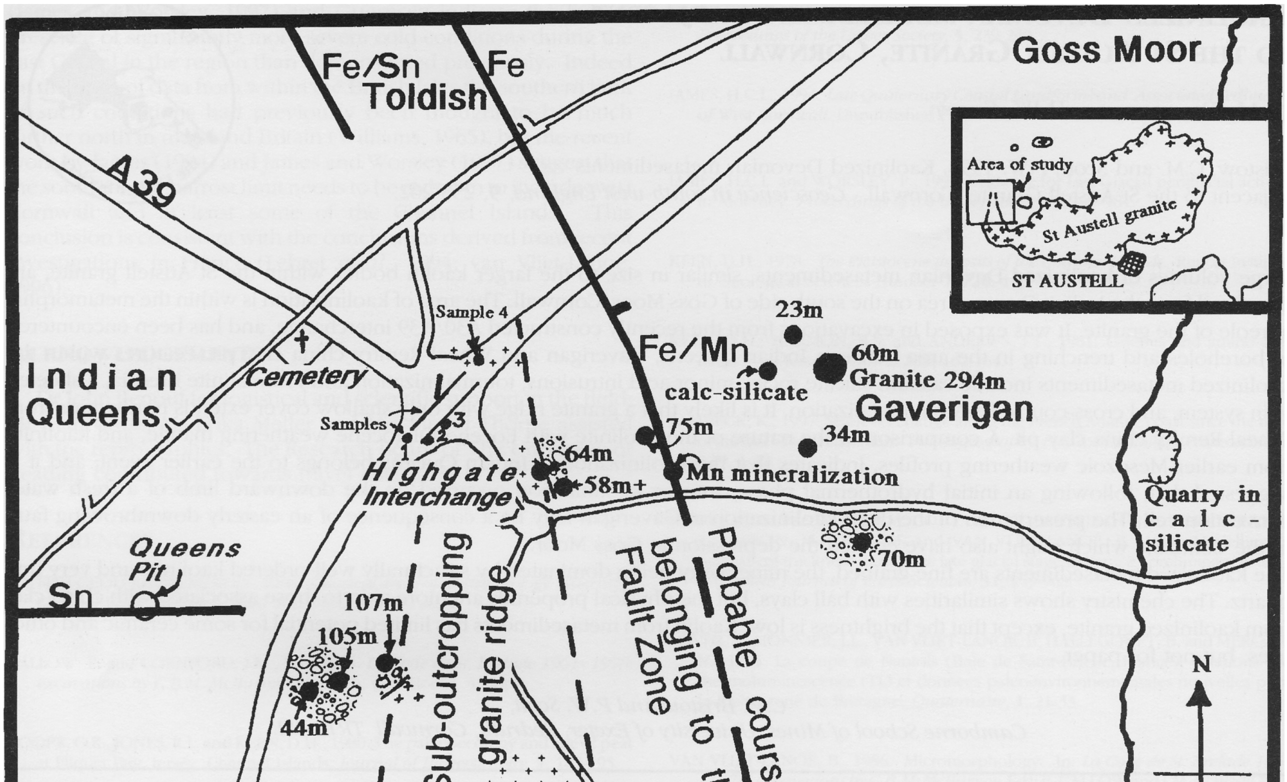

Figure 1. Map of Indian Queens area showing the location of Highgate (A30/A39) interchange and its relation to the western lobe of the St Austell granite. Symbols around boreholes indicate, in general, the lithology encountered in the boreholes. The depth of argillization recorded in each borehole is approximate, as most boreholes (small dots) were inclined. The deep borehole at Gaverigan (large dot) was vertical. Note that the Toldish - Trerice Fe/ Mn lode, which traverses the area from north to south, appears to define an area to the east of the lode where the depth to the granite is much greater than to the west, possibly by as much as 300 m. This suggests that the lode was formed along an important movement plane belonging to the Fal Valley Fault Zone. In the area between the Highgate Interchange and Wheal Remfry china clay pit the granite is probably very close to the surface, with a number of apophyses reaching the surface at least as far north as the area of the interchange.

end of the St Austell granite was intruded at around 270 Ma. In the northern part of Wheal Remfry, a felsitic elvan dyke cuts the microgranite and breccia, making it younger still. This area therefore probably contains some of the youngest granite magmatism in the Cornubian batholith.

In the area to the north of Wheal Remfry, explored by the tin exploration drilling and trenching (Camm and Dominy, 1997), several boreholes encountered tourmalinite breccia similar to that in Wheal Remfry. An attempt to indicate the areas where breccia occurs has been made on Figure 1. The drilling also encountered bands of hard calcium silicate rocks. Extensive tourmalinization of the metapelites near the granite contact is also seen. Both the calcium silicate rocks and the tourmalinized metapelite appear to be resistant to argillic alteration. One of the inclined boreholes went down almost from the collar to 64 m in kaolinized granite, below which it traversed metasediments to 105 m. The granite is variously logged as a porphyry, an elvan, or fine or medium grained granite; it is strongly tourmalinized and there is some development of tourmalinite breccia. The descriptions of the core suggest that the material is very similar to that in the northernmost benches of Wheal Remfry china clay pit, as depicted in Plate 5 of Bristow and Exley (1994). A trench 0.5 km south of the Highgate Interchange found a contact between metasediment and granite, the granite lying on the south-east side.

The profile in the Gaverigan borehole is fairly straightforward, with a steady decrease in the intensity of alteration to a transition to unkaolinized sheared metapelite with many quartz veins and blebs of pyrite at 60 m below surface. The blebs of pyrite decrease in number with depth. Below this the borehole traverses bands of concertina-folded metapelite and calcium silicate rocks, in places intensely tourmalinized, until the granite contact is found at 294 m. The granite below the contact is a fresh or only very slightly kaolinized coarse-grained tourmaline granite.

Further north, in the excavation for the northern bridge of the Highgate Interchange, irregular dyke-like intrusions of what appear to be acid igneous material are present (Figure 2). Because of the intense kaolinization, identification is uncertain, but it more closely resembles the kaolinized microgranite from the northern part of Wheal Remfry than an altered elvan. The intrusions are roughly parallel to the foliation of the metasediments, at approximately 70°. The most reasonable interpretation is that they represent the uppermost apophyses of an underlying granite mass. It would therefore appear that a granite ridge continues northwards from Wheal Remfry towards the Highgate Interchange; however, whether there is a continuous surface outcrop of granite from Wheal Remfry to Highgate is unknown.

This granite ridge is parallel to the Toldish iron/manganese lode and one of the tin exploration boreholes encountered strong iron/manganese mineralization which suggests it intersected an extension of this lode (Figure 1). This lode appears to have formed on the site of a fault with an easterly downthrow, forming part of the Fal Valley Fault Zone (Bristow, 1989), which would help to explain the considerable difference in the height of the granite contact between Gaverigan (294 m below ground level), and Highgate, where the apophyses reach the surface. An easterly downthrow on this fault in the Cenozoic could also have created the depression in which Goss Moor lies.

Both bridge excavations for the Highgate Interchange showed extensive tourmaline veining. In the northern excavation the veining is sub-vertical and striking at 160°, which is approximately at right angles to the foliation of the metapelites (Figure 3). In the southern excavation the strike of the veins is 140°, again almost at right angles to the foliation of the metapelites. (Figure 4). This vein swarm is therefore parallel to the presumed granite ridge and may extend along its crest. This tourmaline veining appears to some extent similar to the sheeted vein systems seen in china clay pits such as Goonbarrow and at Cligga Head, although greisening is less conspicuous at Highgate. There is extensive hematization in places, particularly in the northern bridge excavation. In Figure 5 two late quartz/haemetite veins can be seen displacing earlier tourmaline veins. Much the same arrangement of tourmaline and quartz/haemetite lodes can be seen in the northern stopes of Wheal Remfry (Bristow and Exley, 1994).

KAOLINIZATION IN THE INDIAN QUEENS AREA

Over the whole area, the depth of argillic alteration varies from about 20 m to over 100 m; the deepest alteration being seen in the boreholes drilled closest to Wheal Remfry china clay pit. However, the kaolinization is not confined to the area of the Wheal Remfry - Indian Queens granite ridge, as the Gaverigan borehole, which is some distance east of the Toldish fault, clearly shows.

The calcium silicate rocks appear to be resistant to the argillic alteration process, as the tin exploration drilling showed hard calcium silicate rocks overlying intensely argillized material which had originally been a metapelite. Equally, intensely tourmalinized metapelites also appear to be resistant to argillic alteration, in much the same way as tourmalinized masses in china clay pits are not kaolinized. The argillized metasediment in the tin exploration drilling and the Gaverigan borehole is often a dark grey colour and is frequently coloured red by hematization. The whitest and most intensely argillized material, like that seen in the Highgate excavations, generally lies within 20 m of the surface.

In neither of the Highgate excavations, varying from about 4 m to 10 m below surface, was any unaltered material present, apart from a thin impersistent band of calcium silicate rocks in the excavation for the south-western bridge at Highgate. Most of the argillized metasediment at Highgate is pale greyish-green or pale buff in colour, only occasionally is it near white.

LABORATORY INVESTIGATION OF THE HIGHGATE AND PENHALE SAMPLES

Location and geological context of the samples

Five bulk samples were collected, samples 1-3 from the southwestern bridge excavation at the Highgate Interchange (grid references: 1 - [SW 9236 5901], 2 - [SW 9234 5899], 3 - [SW 9231 5900]). Sample 1 is a kaolinized metasediment, probably originally a slaty rock, which is soft enough to be cut by a penknife. Sample 2 is also a soft, strongly kaolinized metasediment, with tourmaline veins alongside. Sample 3 is similar, but the bulk sample has some acid igneous material as well. Sample 4 [SW 9243 5911] comes from the northeastern bridge excavation; it is also a mixture of soft kaolinized metasediment and acid igneous material.

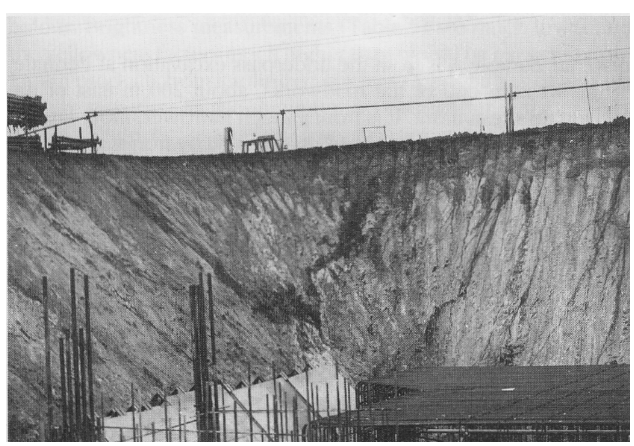

Figure 2. Highgate Interchange. Eastern corner of the southern excavation. Steeply dipping tourmaline veins striking approximately NW-SE in soft, deeply weathered and kaolinized metasediments (sample 3). Paler material in the centre may be a kaolinized acid intrusive concordant with the strike (approx 030°) of the metamorphic foliation, although parent lithology was difficult to establish because of the intense alteration.

Figure 3. Highgate Interchange. Eastern side of the excavation for northern bridge over A39 junction roundabout. Intensely kaolinized metasediments with orthogonal tourmaline veins. The strike of the metamorphic foliation is 070° and the strike of the tourmaline veins is 340°. Hammer for scale at the top of the picture. The ease with which the small stream has cut gullies in the kaolinized metasediment emphasises the softness.

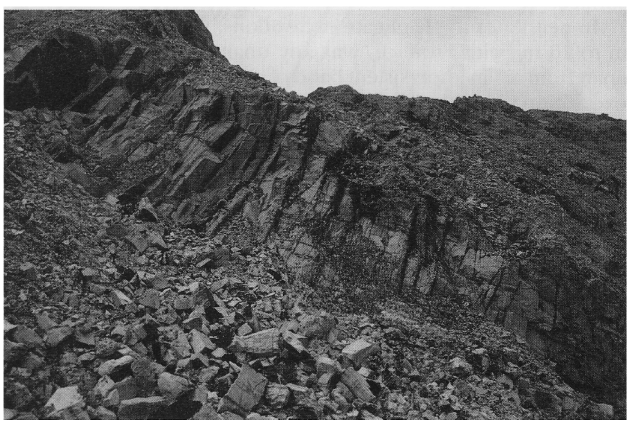

Figure 4. Highgate Interchange. Western corner of excavation for southern bridge over A39 junction roundabout. A sheeted tourmaline vein system striking at 140° in soft intensely kaolinized metasediment. From a distance this looks like the swarms of parallel greisen-bordered tourmaline veins often seen in china clay pits and at locations such as Cligga; but here the kaolinized material was originally a metasediment and the greisen border is rather less conspicuous than is usually the case in granite-hosted examples. Width of field of view is about 6 m.

Sample A is from the underpass excavation at Penhale, at the western end of the roadworks, about 200 m east of the McDonald's restaurant. It is from a much narrower, more limited zone of kaolinization, bounded on one side by iron staining and on the other by relatively unaltered slate. All the samples are from 4 to 6 m below- the original land surface.

Analytical procedures for determining chemical, mineralogical and physical properties

The samples were disaggregated and the particle size distribution determined by sieving and laser sizing (Malvern Sizer). A <10 mm fraction was separated by dispersion, of the <63 μm fraction in water and allowing the coarse material to settle according to Stokes Law. Wet magnetic separation was done using a Boxmag high intensity separator at 25-30amp (>2 Tesla). The morphology of the kaolinite was examined using scanning electron microscopy (JEOL 840): The mineralogy was determined by a combination of optical microscopy and X-ray diffraction, the latter using a Siemens D5000 and CuKa radiation. The crystallinity index was calculated using the method of Hinckley (1963) Using unorientated sample mounts.

Figure 5 Highgate Interchange. Close-up of face on eastern side of excavation fornorthern bridge over the A39 junction roundabout. Intensely kaolinized metasediments (note softness from penknife blade pushed into the strata) and a fine-grained acid intrusion cut by tourmaline veins. Sample 4 taken from near here. Note the absence of greisening. Contact between intrusion and metasediment runs diagonally from top left corner to the bottom of the prominent tourmaline vein, with the intrusion on the left. Tourmaline veins appears to be cut by the acid intrusion, which suggests that the latter is part of the very late magmatic activity which in Wheal Remfry china clay pit is associated with the formation of the hydrothermal breccia (see Bristow and Howe, 1995). A late 'Stage IV' iron vein (see Bristow and Exley, 1994) runs across the centre of the picture, displacing the tourmaline veins in a manner reminiscent of those seen in Wheal Remfry (op cit, *Plate 5, 279).*

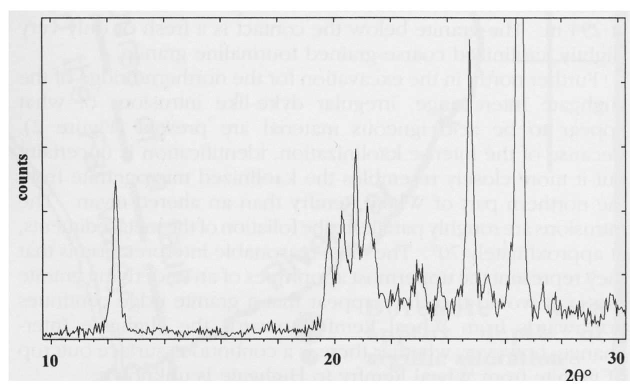

Figure 6. Part of X-ray diffraction trace of <10 μm fraction of sample 2. Note the sharp nature of the diffraction maxima in the region 19-22° 2θ, indicating a high degree of crystallinity of the kaolinite.

Chemical analysis was made by X-ray fluorescence spectrometry (Philips PW1400) and a fusion bead technique. Brightness measurement was by Elrepho Reflectance Spectrophotometer. The modulus of rupture measurements were made on bars dried at 110°C, using an industry standard technique, described in Ryan and Radford (1987). Liquid limit and plastic limit were determined according to BS1377: Part 2: 1990 on a bulk sample of <63 μm material made from combining equal amounts of samples 1-4.

Particle size distribution

The kaolinized metasediments is almost entirely <1 mm with around 90% <63 μm (Table. 1). This contrasts with a fully kaolinized granite which has around 70% >1 mm. The sand, gravel and coarse rock fractions found in granite-hosted china clay, matrix are completely absent here. However, the <2 μm: fraction is comparable in amount to that from a kaolinized granite, indicating a much higher content of particles in the particle size range 2 to 63 μm in the kaolinized metasediments. Much of this material appears to be in the form of large stacks of .kaolinite.

Table 1. Summary of particle size distribution of kaolinized metasediments.

Sample	1	2	3	4	A
%<1.00 mm	99.5	99.4	99.7	95.2	99.7
%<63 µm	96.3	93.7	97	84.4	89.1
%<10 µm	51	48	68	49	48
%<2 µm	12	13	24	10	7

Mineralogy

The coarse (>63 µm) fractions are composed largely of variable amounts of quartz, tourmaline, and undispersed 'white slate' fragments (Table 2). X-ray diffraction shows the latter to be a mixture of mica and kaolinite. Quartz/tourmaline vein fragments (samples 1 and 2) occur, and fragments resembling fine grained igneous material and quartz crystals of possible igneous origin are also present (samples 3 and 4). Ferruginous vein material is also sometimes found.

The <63µm fraction is dominated by kaolinite with variable amounts of fine quartz (Table 2), no doubt reflecting a fine silica fraction inherited from the pelitic parent. This quartz content is more than would be associated with a similar size fraction from a kaolinized granite. Minor and trace amounts of K-feldspar and mica occur, and surprisingly sample A contains Na-feldspar, presumably as relict unkaolinized material. Extraction of the heavy minerals from the <63 µm fraction showed cassiterite, monazite and zircon. The <10 µm fraction compares with the size distribution of kaolin used in the paper industry. It contains mainly kaolinite as expected, but significant very fine quartz, more than would be acceptable in the paper industry, occurs. A typical X-ray diffraction trace is shown in Figure 6. The kaolinite has a well ordered crystal structure as indicated by the sharp nature of the diffraction maxima in the region 19-22°2θ. Hinckley crystallinity indices (Table 3) give values similar to those of commercial china clays from kaolinized granite. Ball clays from Devon and the Palaeogene weathering mantle on the Culm metasediments in North Devon (Robson, 1993) have a much lower crystallinity index. The ball clays form by the accumulation of sediment derived from Palaeogene chemical weathering of various Palaeozoic rocks, including the Culm, and granites (Bristow and Robson, 1994). This suggests that the conditions which produced the Indian Queens kaolinite might be different from those which generated the parent material for ball clays, although transportation (simulated by extended grinding in the laboratory) is known to create increased disorder in the crystal structure.

The presence of kaolinite in two forms is shown in Figure 7. Large stacks up to 30 pm across are present (Figure 7a), and a large proportion of the kaolinite is in this form. These have a similar appearance but are overall smaller than the very large curled stacks (up to100 µm) found in kaolinized granite. Much finer (0.5 µm across) pseudo-hexagonal platelets of kaolinite are also found, typically adhering to the larger stacks (Figure 7b). These are similar to the smaller kaolinite crystals present in kaolinized granite.

Chemistry

There is some variation in the chemistry of the <63 µm and <10 µm fractions between samples (Table 4), particularly in SiO_2, Fe_2O_3, TiO_2 and K_2O, reflecting the differences in proportions of the main minerals. A typical commercial ceramic china clay is shown for comparison with the <10 µm fraction; both have similar particle size distributions. Other data for comparison are given in Bloodworth *et al.* (1993). Two typical ball clays are also shown in Table 4. The ball clays have very different particle size distributions from the Indian Queens material with a high proportion of ultrafine particles (around 50-60% <1 µm). The TiO_2 content is typical of that found in deposits formed by kaolinization of pelitic rocks and is similar to that in the ball clays, rather than china clay from kaolinized granite. Samples with higher amounts of Fe_2O_3 reflect the buff colour of these powders.

Table 2. Summary of mineralogy of kaolinized metasediments by optical microscopy

and X-ray diffraction.

Sample	>63 µm	<63 µm major phase	<63 µm minor phase	<63 µm trace phase
1	quartz, tourmaline, `white slate', rare Fe oxides	kaolinite, quartz,	mica	-
2	quartz, tourmaline, `white slate', rare Fe oxides	quartz, kaolinite	mica	K-feldspar tourmaline
3	quartz, tourmaline, `white slate', Fe oxides	kaolinite	quartz	K-feldspar, mica
4	quartz, tourmaline `white 'slate', rare Fe oxides	kaolinite	quartz	mica, tourmaline
A	'white slate', quartz, tourmaline, Fe oxides	quartz	kaolinite, mica	Na-feldspar

<10 µm fraction by X-ray diffraction

Sample	major phase	minor phase	trace phase
1	kaolinite	quartz	-
2	kaolinite	quartz	mica
3	kaolinite	-	quartz, mica
4	kaolinite	quartz	-
A	kaolinite, quartz	mica	Na-feldspar

Only minor reduction in the Fe_2O_3 content occurs by separation of the <10 µm fraction.

SiO_2 in the <10 µm material is variable, but Al_2O_3 is lower than in china clay, reflecting a lower kaolinite content. The proximity of calcium silicate rocks is not reflected in the CaO values of the kaolinized material. K_2O shows some variation, reflecting the differences in the mica content. Amounts are similar in both the <63 µm and <10 µm size fractions, indicating that small amounts of mica occur in all sizes and the mineral is not preferentially concentrated in larger sizes as with kaolinized granite.

Overall, the chemistry of the Indian Queens material shows similarities with the ball clays. This is not surprising as both have been derived from pelitic rocks. The lower K_2O and CaO values here suggest that the chemistry of the alteration process was more intense than the Palaeogene weathering that produced the ball clays and also the alteration that produced the china clay.

Physical properties

The <63 µm and <10 µm fractions vary from an off-white to buff colour. Brightness measurements (Table 5) are much lower and the yellowness factors much higher than would be expected from kaolin products from kaolinized granites. A brightness of >80% is usually regarded as the minimum acceptable for a paper filler kaolin. Magnetic separation does not appear to improve the brightness, although the magnetic fraction was strongly coloured due to the presence of iron oxide minerals. Chemical bleaching to improve the brightness has not been attempted. The presence of significant amounts of quartz in the <10 µm fractions, allied with some samples having SiO_2 present in significantly greater amounts than in china clay products, would suggest that abrasion would be a problem in paper clay applications.

Table 3. Hinckley crystallinity indices for kaolinite from kaolinized metasediments.

Sample	1	2	3	4	A	China Clay*	Ball Clay+
Hinckley Index	1.2	1.45	1.23	1.53	1.16	1.2 - 1.4	0.68

* Typical range of values for paper filler and coating grade china clay

+ EWVA ball clay from South Devon

Table 4. Chemical analyses of <63 pm and <10 pm size fractions of kaolinized metasediments. **CCC**, ceramic china clay (Remblend). **BCN**, ball clay, North Devon. **BCS**, ball clay, South Devon (Hycast). nd, below detection limit. LOI, loss on ignition.

<63 µm fraction

%	1	2	3	4	A
SiO2	60.14	61.9	41.95	46.56	63.21
TiO2	1.21	1.13	5.54	3.92	1.16
Al2O3	26.18	24.13	32.73	31.53	23.06
Fe2O3	0.54	0.73	2.62	1.69	1
MnO	nd	nd	0.03	0.02	nd
MgO	0.23	0.91	0.2	0.49	0.54
CaO	0.03	0.08	0.07	0.07	0.01
Na2O	0.16	0.43	0.14	0.29	0.24
K2O	0.84	1.2	0.88	0.38	4.13
BaO	0.01	0.01	0.22	0.04	0.05
F2O3	0.06	0.03	0.49	0.12	0.07
SO3	nd	nd	0.02	nd	nd
LOI	10.27	8.3	14.32	13.52	6.2
Total	99.78	98.87	99.19	98.63	99.66

<10 µm fraction

%	1	2	3	4	A	CCC	BCN	BCS
SiO2	57.45	56.72	42.57	46.74	60.25	48	63	52
TiO2	1.34	1.06	5.24	3.07	1.23	0.05	1.5	1
Al2O3	28.47	28.65	33.44	34.02	25.24	37	24	31
Fe2O3	0.46	0.54	2.55	1.2	0.95	0.8	0.9	1.2
MnO	nd	0.01	0.03	0.01	0.01	-	-	-
MgO	0.13	0.47	0.11	0.15	0.45	0.3	0.4	0.4
CaO	0.02	0.04	0.04	0.02	0.01	0.06	0.2	0.2
Na2O	0.13	0.21	nd	0.1	0.2	0.1	0.4	0.2
K2O	0.66	1.45	0.9	0.39	4.51	1.9	2.3	2.1
BaO	0.01	0.03	0.24	0.05	0.12	-	-	-
P2O3	0.07	0.05	0.49	0.13	0.1	-	-	-
SO3	0.04	0.02	0.1	0.04	nd	-	-	-
LOI	10.53	9.76	13.43	13.04	6.11	12.1	-	-
Total	99.32	99	99.14	98.95	99.17	-	-	-

The modulus of rupture (MOR) data (Table 5) show considerable variation, and although the <2 µm size fraction is not a reliable indication of the likely MOR (Scott *et al.,* 1996), there does appear to be a broad correlation. The Highgate samples (1-4) have comparable MOR values to some of the weaker china clays (MOR = 7 to 16 kgf/cm^2) used in the ceramic industry for sanitary ware, but values are substantially lower than those associated with the much stronger ball clays (MOR = 25 to 100 kgf/cm^2). A low plasticity of the <63 µm fraction compared with ball clays, is indicated by the plastic and liquid limit data (Table 5); but the data fall into the box of 'acceptable' forming properties in the clay workability chart of Bain and Highley (1978) (see also Harrison and Bloodworth, 1994).

COMPARISON OF KAOLINIZED METASEDIMENTS WITH COMMERCIAL BALL CLAY AND CHINA CLAY

The above data show that kaolinized metasediments have some similar characteristics to ball clays, particularly in their chemistry, but in other properties they are similar to some china clays from kaolinized granite. They have little potential for being a source of kaolin for paper use as, although kaolinite with a highly ordered crystal structure is present, there are significant amounts of very fine-grained quartz, which would create abrasion in the paper-making process, and the colour characteristics are poor. The low brightness would also restrict the uses of the clay for many ceramic purposes, and beneficiation as illustrated by the colour values after magnetic separation is unlikely to give much improvement. The MOR and plasticity data, however, indicate that kaolinized metasediments may have suitable properties for some low value ceramic applications, such as bricks and tiles, where the whole material is used. Further laboratory work making ceramic bodies and test firing of samples would be needed to confirm this. Also, a more thorough examination of the extent any area of kaolinized metasediment would be essential before any resource is identified. It is known that one past commercial application for this kind of material was for brickmaking at the now defunct Carbis brickworks, between Roche and Bugle.

KAOLINIZATION OF DEVONIAN STRATA ELSEWHERE IN CORNWALL

There is evidence for the existence of kaolinization of the Devonian strata elsewhere in many places in Cornwall. The presence of the brickworks at Carbis may indicate that kaolinization of the aureole rocks of the St Austell granite extends eastwards along the south side of Goss Moor, past Roche and through Carbis. Sabine (1968) described a pale coloured kaolinitic material which occurred alongside the Perran iron lode which was formerly commercially exploited as "Treamble Fuller's Earth". He attributed the occurrence to oxidation of sulphides in the lode during weathering releasing sulphuric acid, which accelerated the kaolinization of the wall rocks. Pale-coloured kaolinized slate was seen in the excavations for the Bodmin by-pass in the vicinity of Carminow Cross [SX 089 657]. This occurrence is situated some distance from the nearest granite (3 km), and well outside the metamorphic aureole. Intense kaolinization of Devonian slate was seen in an excavation for roadworks a quarter of a mile northeast of Lostwithiel [SX 110 603], and somewhat less intense kaolinization accompanied by intense bleaching was seen in a temporary excavation at Porthpean beach [SX 0316 5080]. A zone of soft white kaolinized slate is reported to be exposed on Porthpean beach under certain conditions of low tide and low sand levels, although the authors cannot claim to have seen it. Both the Lostwithiel and Porthpean occurrences are adjacent to the suspected position of major faults, which could have facilitated the circulation of meteoric water in the vicinity.

Intense kaolinization of an elvan has been seen on the Sticker by-pass [SX 977 507] and intense kaolinization of slates was noted near Scorrier beside the A30 [SW 722 443]. An occurrence of 'white slate' over an area of 0.2km^2 with a chemical composition very similar to the Highgate material was recorded by Polkinghorne (1947) near Redmoor mine, Callington, which was exploited during the Second World War for the construction of temporary air strips. These and other examples of pockets of kaolinized slate and associated rocks are distinguishable from Quaternary weathering by the presence of kaolinite, pale colour and extreme softness.

Table 5. Colour measurement, modulus of rupture and plasticity of kaolinized metasediments.

<10 µm size fraction					
Sample	**1**	**2**	**3**	**4**	**A**
Brightness (reflectance at 457 nm)	67.6	71.9	67.9	59.9	63
Yellowness (reflectance 570-457 nm)	10.2	7.7	6.3	16.2	11.6
Non-magnetic <63 pm size fraction					
Sample	**1**	**2**	**3**	**4**	**A**
Slightness % (reflectance at 457 nm)	67.4	67.8	71	61.7	61.1
Yellowness % (reflectance 570-457 nm)	10.4	7.4	8.7	15.6	11.6
Modulus of rupture kgf/cm2 (after drying at 110°C)	7.49	5.12	14.36	6.95	2.26
Plastic limit %	composite sample		34.3		
Liquid limit %	composite sample		47.1		

IMPLICATIONS FOR GENESIS OF THE INDIAN QUEENS KAOLIN

A comparison with the Eocene/Oligocene weathering mantle preserved in the ball clay pit at Woolladon, north Devon, shows that the nature of the kaolinite there (b-axis disordered) is quite different from Indian Queens (well ordered), thereby suggesting that different processes of weathering may be involved. A review of ball clay and kaolin deposits of Europe and North America (Bristow, 1990) shows that b-axis disordered kaolinite is characteristic of late Eocene and

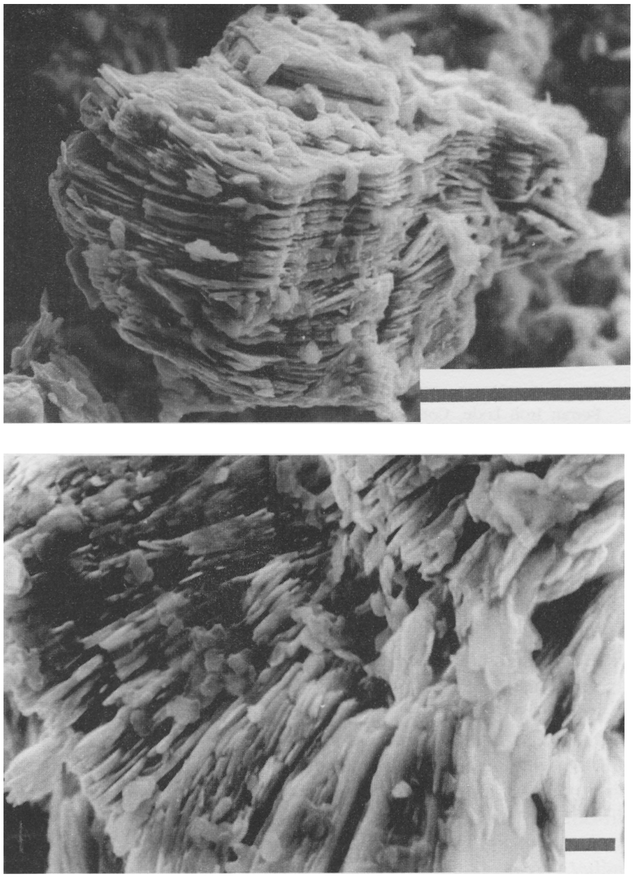

Figure 7. Scanning electron micrographs of kaolinite from kaolinized metasediment. a, large stack of kaolinite (Sample 2. Scale bar 10 µm). b, detail of a large stack of kaolinite with adhering small (0.5 µm) well crystallized kaolinite platelets (Sample 2. Scale bar 1 µm).

Oligocene weathering profiles in both continents. However, earlier weathering profiles formed in the Mesozoic and earliest Tertiary (Palaeocene) in places as far apart as southern Sweden, central Europe, Ukraine, Appalachians, Idaho, Minnesota and the Moose River Basin of Ontario contain comparatively coarse well ordered kaolinite like that at Indian Queens. Some of these weathering profiles are overlain by late Cretaceous sediments, suggesting an intensive weathering event earlier in the Cretaceous or in the late Jurassic.

The granite ridge extending northwards from Wheal Remfry towards Indian Queens could have been the site of a china clay-type convection cell. It is therefore suggested that the most likely scenario for the generation of the kaolinized Devonian sediments between Wheal Remfry and Highgate involves an initial phase of hydrothermal 'softening up' soon after the latest phase of the St Austell granite was intruded. This was followed by the establishment of a fresh water convection cell, of a similar size to that in kaolinized granite, with the kaolinization occurring on the downward limb. This may be related to the development of one or more deep weathering episodes associated with the development of a planation surface throughout Cornwall in the late Jurassic/early Cretaceous/earliest Tertiary. As with the genesis of china clays, there may be a multistage series of fluid processes. The chemistry of the Indian Queens material suggests that the kaolinizing process was more intense than that which produced the parent material for ball clays. There is even a suggestion that it was more intense than kaolinization in the granites.

The profile in the Gaverigan borehole, however, looks much more like the direct product of weathering, and a comparison with the genesis of the "Treamble Fullers Earth" (a kaolinitic material) is worth considering. Sabine's (1968) suggestion that oxidation of sulphides in the Perran iron lode released sulphuric acid, thereby causing accelerated kaolinization of the wall rocks alongside the lode, may be relevant. The extensive occurrence of pyrite impregnating the metasediments below the weathering profile at Gaverigan suggests that a similar process could have operated there. It is also possible that the very thick sequence of kaolinized metasediments has been preserved by being downfaulted by an easterly downthrow in the Cenozoic on the Fal Valley Fault Zone. This faulting could also have created the depression now occupied by Goss Moor. Drilling reported by Collins (1912, p380) in the south-western part of Goss Moor showed up to 20 m of sediments overlying deeply weathered metasediments. These included 12 m of sedimentary kaolin overlying pyritous tin-bearing sediments. This suggests that there could concieveably be some pre-Quaternary material deposited in a shallow basin on the downthrow side of the Toldish-Trerice fault.

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REFERENCES

ALLMAN-WARD, P., HALLS. C., RANKIN, A.H. and BRISTOW, C.M. 1982. An intrusive hydrothermal breccia body at Wheal Remfry in the western part of the St Austell granite pluton, Cornwall. Pp. 1-28 in EVANS, A.M. *Metallization associated with acid magmatism.,* John Wiley and Sons.

BAIN, J.A. and HIGHLEY, D.E. 1978. Regional appraisal of clay resources - a challenge to the clay mineralogist. *Proceedings of the International Clay Conference, Oxford,* pp.437-446.

BLOODWORTH, A.J., HIGHLEY, D.E. and MITCHELL, C.J. 1993. *Industrial Minerals Laboratory Manual: Kaolin.* British Geological Survey Technical Report, WG/93/ 1, 76pp.

BRITISH STANDARD 1377:1990. Part 2. *Methods of testing soils for engineering purposes.* British Standards Institution.

BRISTOW, C.M. 1968. Kaolin Deposits of the United Kingdom and Northern Ireland. *23rd International Geological Congress, Prague,* **15**, 275-288.

BRISTOW, C.M. 1989. The Fal Valley Lineaments. *Camborne School of Mines Journal,* **89**, 34-42.

BRISTOW, C.M. 1990. Ball clays, weathering and climate. *Proceedings of the 24th Forum on the geology of industrial minerals,* May 2-5, 1988, Greenville, North Carolina, published by the South Carolina Geological Survey, 25-37.

BRISTOW, C.M. and EXLEY, C.S. 1994. Historical and Geological Aspects of the China Clay Industry of South-west England. *Transactions of the Royal Geological Society of Cornwall,* **21**, 247-314.

BRISTOW, C.M. and HOWE, J.H. 1995. Field excursion to the Fal Valley, in the western part of the St Austell granite, 4th January, 1995. *Proceedings of the Ussher Society,* **8**, 454-455.

BRISTOW, C.M. and ROBSON, J.L. 1994. Palaeogene basin development in Devon. *Transactions of the Institution of Mining and Metallurgy* (Section B: Applied Earth Science), **103**, B163-174.

CAMM, G.S. and DOMINY, S.C. 1997. Metasediment-hosted tin mineralization in the Indian Queens area, mid-Cornwall. *Proceedings of the Ussher Society,* **9,** 211-214.

CHESLEY, J.T., HALLIDAY, A.N., SNEE, L.W., MEZGER, K., SHEPHERD, T.J. and SCRIVENER, R.C. 1993. Thermochronology of the Cornubian batholith in southwest England: Implications for pluton emplacement and protracted hydrothermal mineralization. *Geochemica et Cosmochemica Acta,* **57**, 18171835.

COLLINS, J.H. 1912. Observations on the West of England Mining Region, being an account of the mineral deposits and economic geology of the region. *Transactions of the Royal Geological Society of Cornwall*,**14**; facsimile reprint, Cornish Mining Classics, Truro, 1988.

DARBYSHIRE, D.P.F. and SHEPHERD, T.J. 1994. Nd and Sr isotope constraints on the origin of the Cornubian batholith SW England. *Journal of the Geological Society*, **151**, 795-802.

EXLEY, C.S. 1959. Magmatic differentiation and alteration in the St Austell granite. *Quarterly Journal of the Geological Society of London*, **114**, 197-230.

HARRISON, D.J. and BLOODWORTH, A.J. 1994. *Industrial Minerals Laboratory Manual: Construction materials.* British Geological Survey Technical Report, WG/94/12, 100pp.

HINCKLEY, D.N., 1963. Variability in 'crystallinity' values among the kaolin deposits of the coastal plain of Georgia and South Carolina. *Clays and clay minerals,* **11**, 229-235.

POLKINGHORNE, J.R. 1947. Slate mining at Redmoor. *Transactions of the Royal Geological Society of Cornwall*, **17**, 269-271.

ROBSON, J.R. 1993. *Mineralogical, geochemical and geological examination of the Woolladon ball claypit within the Petrockstow Basin, North Devon*. Unpublished MSc Thesis, University of Exeter, 99pp.

RYAN, W. and RADFORD, C. 1987. *Whitewares: production, testing and quality control*. Pergamon Press on behalf of Institute of Ceramics, 333pp.

SABINE, P.A. 1968. Origin and age of solutions causing the wallrock alteration of the Perran Iron Lode, Cornwall. *Transactions of the Institution of Mining and Metallurgy,* (Section B: Applied Earth Sciences), **77**, B1-5.

SCOTT, P.W., HART, F.W. and SMITH, D. 1996. The quantitative mineralogy of ceramic grade kaolin from the St Austell Granite and its relationship to chemistry and physical properties. *Proceedings of the Ussher Society,* **9**, 91-96.