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KAOLINISATION, MINERALISATION AND STRUCTURES IN BIOTITE GRANITE AT BODELVA, ST. AUSTELL, CORNWALL

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Bodelva China Clay Pit until recently was providing kaolin for the paper and other industries and at closure was yielding around 40,000 tonnes per annum of product. It is entirely located within the medium to coarse grained biotite rich facies of the eastern part of the St. Austell granite. Four distinct stages of alteration have been delineated: slightly, medium, highly and completely altered biotite granite. These occur together with minor exposures of fine grained biotite granite and a few areas of primary greisening. Various types of mineralised veins and dykes are widespread throughout the china clay pit and follow mainly west-south-west — east-north-east and north-north-west — south-south-east trends respectively. Two major sets of iron oxide stained fracture zones, following the same trends are spatially related to completely altered biotite granite. There is strong evidence for the extreme form of kaolinisation within these areas being predominantly structurally controlled. The intense iron oxide staining along the southern rim of the pit is considered a result of de-ferruginisation of biotite. Analyses of micas show an almost continuous trend of compositions, represented by changes in the cation distributions in octahedral sites from tri-octahedral (Fe+Mn+Mg rich) biotite to di-octahedral (Al rich and Fe+Mn+Mg poor) types approaching stoichiometric muscovite.

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INTRODUCTION

Bodelva China Clay Pit is situated on the south-eastern edge of the St. Austell granite, Cornwall [SX 049 548]. It covers an area of approximately 0.5 km^2. Until recently it was producing kaolin for the paper and other industries. Production ceased in September, 1998, and the site is currently being redeveloped for the Eden Project. This is a series of large, super-strong, polymer covered, steel-framed domes containing flora from various climatic zones, along with associated educational and visitor facilities.

Most of the working china clay pits in the St. Austell area are in the central and western parts of the granite (Bristow and Exley, 1994; Manning *et al.*, 1996) (Figure 1) which is made up mainly of lithium mica, tourmaline and topaz granites. Bodelva China Clay Pit was unique in being the only operating one in the eastern biotite granite. The objective of this work is to record the major geological features in the pit before it ceased to be available for study. This has included establishing the variations in the granite, the different stages of alteration in the formation of kaolinite, the other types of mineralisation and structural features within the pit. The significance of these to our understanding of the geological history of the St. Austell granite is discussed.

The St. Austell granite has attracted many researchers over the last half century (e.g. Exley 1959; Exley and Stone, 1982; Hill and Manning, 1987; Bristow and Exley, 1994) and considerable lithological variation is now recognised within the pluton. Most recently, Manning *et al.* (1996) describe six granite types based on differences in mineralogy and texture. These are biotite granite, lithium mica granite, globular quartz tourmaline granite, equigranular tourmaline granite, fine-grained tourmaline granite, and topaz granite. They describe the biotite granite as making up 70% of the outcrop and corresponding to the coarsely porphyritic types in the Lands End and Dartmoor granites. It is coarse grained with microperthitic K-feldspar megacrysts and a hypidiomorphic granular texture. The sequence of mineralisation and alteration affecting the St. Austell granite have been reviewed by Bristow and Exley (1994) and Psyrillos *et al.* (1998). These include greisening and tourmalinisation with associated Sn, W and Cu mineralisation, Fe, U, Pb and Zn mineralisation associated with a first phase of argillic alteration, and a later extensive kaolinisation. Further mineralisation is associated with emplacement of felsite dykes ('elvans'). Bristow and Exley (1994) and Psyrillos *et al.* (1998) differ in favouring low and high salinity fluids, respectively, as responsible for the kaolinisation, although both sets of authors emphasise the low temperatures (30-200°C and <100°C respectively) during this event. Isotopic evidence indicates that the fluids responsible for the kaolinisation are meteoric in origin (Sheppard, 1977).

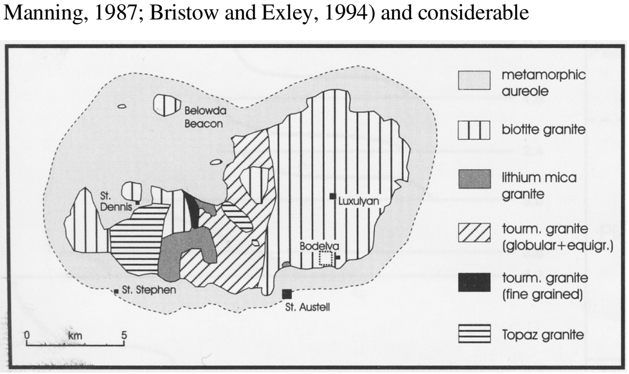

Figure 1. *Distribution of granite varieties in the St. Austell Granite (after Manning et al. 1996) and location of Bodelva China Clay Pit.*

HISTORY OF MINERAL EXTRACTION AT BODELVA

Little is recorded of the earliest clay workings in the Bodelva area but there were probably several small pits working in the early part of the 19th century. The mining records of the Royal Geological Society of Cornwall in 1858 mention a Wheal Carlyon Pit as producing 500 tons of clay a year. In the early 20th century cassiterite was extracted as a by-product along with china clay. Hard vein material, left behind after the hydraulic mining of the clay, was crushed using water-driven 'stamps' and the ore separated by gravity methods. Apparently, the revenue from the sale of the tin concentrate paid for the wages of the clay workers. In the 1970s, several mining companies made sampling surveys for cassiterite in the pit, and although ore was found, particularly in quartz-rich veins in the west of the pit, the grade was low and mineralisation too sporadic for commercial extraction, even with the high price of tin pertaining at that time.

For the last 30 years Bodelva pit produced china clay mainly for the paper industry, particularly filler grades for magazine papers such as 'weekend colour supplements'. In the mid-1980s a special clay was developed for the coating of rotogravure printing paper. This was produced by partially delaminating the 'book' structure shaped kaolin particles which are fairly abundant in the kaolinised granite. The special property this clay gives to the paper coating formulation is considered to be due to the relatively high aspect ratio of the delaminated clay particles for their relatively coarse particle size. During the last few years of operation, the annual clay production rate reached 40,000 tonnes.

For mineral specimen collectors, Bodelva China Clay Pit is well known for its veins of amethystine quartz, sometimes found on the east side of the pit, for its honey coloured cassiterite, which occurred sporadically in quartz-tourmaline veins, and particularly for its 'pigs eggs'. The latter are large (up to 10 cm in length) K-feldspar megacrysts which often show various forms of twinning. They could be extracted whole from the partly kaolinised granite. Elongate black tourmaline crystals ('shorl') also have been found.

GEOLOGY AND CLASSIFICATION OF ALTERATION STAGES

The two major geological features at Bodelva are the variable degree of kaolinisation, and the large area of reddish-brown iron oxide stained completely altered granite along the southern margin of the pit. Other features of importance are small areas of greisening, a few patches of fine grained biotite granite and a widespread distribution of mineralised veins. At the time of survey there were large areas of exposure, but significant parts of the pit were covered by sand tips or overburden and there had been some back-filling.

Four stages of alteration have been recognised. These are slightly altered biotite granite, medium and highly altered, and completely altered biotite granite. Unaltered biotite granite, showing no evidence of secondary minerals, is not present. The criteria used in the field for determining the different stages are the rock fabric, colour changes, decomposition of minerals (plagioclase, K-feldspar and biotite) and changes in the structural integrity of the rock, such as hardness and consistency. These differences are reflected in mineralogical and textural variations visible in thin section, which are summarised in Table 1. These stages are not too dissimilar from some existing classifications of rock mass weathering or alteration in tropical or sub-tropical climatic zones, for example those described in Dearman (1976) and Irfan (1981). However, these other classifications are designed for use in describing differences in the engineering properties. The sequence of alteration described by Psyrillos *et al. (1998),*

	slightly altered	medium altered	highly altered	completely altered
igneous texture preserved	←	—	→	
relict plagioclase	←	→		
plagioclase twinning visible	↔			
relict K-feldspar	←	—	→	
isotropic K-feldspar			↔	
unaltered biotite	←	→		
de-ferruginized biotite	←	—	→	
primary white mica	←	—	—	→
secondary white mica	←	—	—	→
fine grained mica (sericite) + kaolinite pseudomorphing feldspars	←	—	—	→
kaolinite rich matrix			←	→
kaolinite stacks occur		←	—	→
fine disseminated Fe-oxides occur			←	→
quartz	←	—	—	→
angular broken quartz			←	→
tourmaline	←	—	—	→

Table 1. *Mineralogical and textural changes with different degree of kaolinisation.*

%	1	2	3	4	5
SiO_2	36.58	40.76	39.05	41.61	46.44
TiO_2	2.44	1.15	1.82	1.3	0.59
Al_2O_3	21.4	23.92	32.22	24.14	32.03
FeO	20.88	16.3	17.88	15.99	3.68
MnO	0.55	0.75	0.55	0.51	0.22
MgO	4.14	2.29	2.52	2.15	1.74
Na_2O	0.41	0.28	nd	nd	0.78
K_2O	9.75	10.33	9.8	10.1	10.34
Cl	0.32	nd	nd	nd	nd
Total	96.47	95.78	95.5	95.8	95.82
Number of ions on the basis of 22 oxygen					
Si	5.546	5.9751	5.8171	6.0503	6.245
Al(Tet)	2.454	2.0249	2.1829	1.9497	1.755
Al(Oct)	1.3699	2.1077	1.8937	2.1872	3.3213
Ti	0.2782	0.1268	0.2039	0.1421	0.0597
Fe^{2+}	2.6474	1.9983	2.2848	1.9444	0.1438
Mn	0.0706	0.0931	0.0934	0.0628	0.0251
Mg	0.9356	0.5004	0.544	0.466	0.3488
Na	0.1205	0.0796	-	-	0.2034
K	1.8857	1.9317	1.8622	1.8734	1.7737
Cl	0.0822	-	-	-	-
$\sum$Tet	8	8	8	8	8
$\sum$Oct	5.3017	4.8263	5.0198	4.8025	4.1687
$\sum$inter	2.0062	2.0113	1.8622	1.8734	1.9771

%	6	7	8	9	10
SiO_2	46.6	47.42	46.54	48.14	47.88
TiO_2	1.24	0.75	0.26	nd	nd
Al_2O_3	29.2	32.2	33.27	34.57	34.64
FeO	6.15	4.01	2.92	0.96	0.83
MnO	0.28	nd	nd	nd	nd
MgO	1.85	0.88	1.31	0.29	0.37
Na_2O	0.34	0.34	0.55	nd	0.26
K_2O	10.46	10.81	10.58	9.7	9.84
Cl	nd	nd	nd	nd	nd
Total	96.12	96.41	95.43	93.66	93.82
Number of ions on the basis of 22 oxygen					
Si	6.3352	6.331	6.2446	6.4258	6.3928
Al(Tet)	1.6648	1.669	1.7554	1.5742	1.6072
Al(Oct)	3.0138	3.3977	3.5058	3.8643	3.8437
Ti	0.1268	0.0753	0.026	-	-
Fe^{2+}	0.6992	0.4477	0.3277	0.1072	0.0927
Mn	0.0322	-	--	-	
Mg	0.3749	0.1751	0.262	0.0577	0.0736
Na	0.0896	0.088	0.1431	-	0.0673
K	1.814	1.841	1.8109	1.6516	-
Cl	-	-	-	-	-
$\sum$Tet	8	8	8	8	8
$\sum$Oct	4.2469	4.0958	4.1217	4.0292	4.01
$\sum$Inter	1.9036	1.929	1.954	1.6516	1.7432

Table 2. *Mineral chemistry and chemical formula of micas from Bodelva China Clay Pit. 1-2, primary biotite. 3-4, core of biotite within muscovite. 5-6, muscovite surrounding core of biotite. 7-8, primary muscovite. 910, secondary muscovite. nd = below detection limit. CaO is below detection limit throughout. $\sum$Tet = sum of tetrahedral sites. $\sum$Oct = sum of octahedral sites. $\sum$Inter = sum of interlayer sites.*

from unaltered to completely altered granite is rather different to that given here as their differences in the degree of kaolinisation relate only to feldspar dissolution.

Slightly altered biotite granite is recognised by being relatively hard with a pale orange discolouration on the rock surface. It cannot be broken by hand. The large white or pale rose coloured K-feldspar crystals often impart a shiny lustre, whereas plagioclase tends to be slightly lighter in colour with a cloudy appearance. Both types of feldspar show signs of early alteration. Secondary white mica (sericite) forms within microfractures of micro- to mesoperthitic orthoclase. Plagioclase tends to be more altered. Typical lamellae of multiple twinning are only sparsely preserved and in most cases are already replaced by a mixture of microcrystalline sericite and kaolinite. However the general mineral forms and shapes are still present and the igneous texture is preserved.

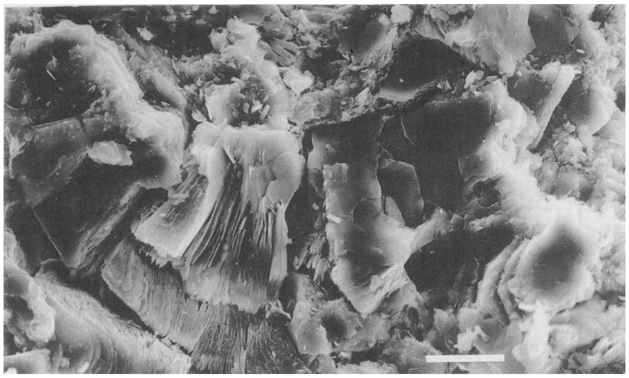

Figure 2. SEM micrograph of highly altered biotite granite showing typical curled stacks of kaolinite interlayered with secondary white mica (sericite). Scale bar = 10 μm.

Two primary micas are present in the slightly altered granite. Brown mica, approaching biotite in composition (Table 2), usually occurs as discrete crystals or in aggregates formed by large flakes (up to 1 cm in diameter). They frequently contain inclusions of zircon, which are usually surrounded by pleochroic haloes. Some of the brown mica show evidence of alteration (referred to here as de-ferruginisation), occurring as cores and isolated patches within crystallographically contiguous white mica crystals. The mineral chemistry of the micas is discussed later. Primary white mica is slightly less abundant than brown mica and tends to occur in clear, often ragged flakes or along the rims of, or intergrown with biotite. Tourmaline is a common constituent occurring as euhedral to subhedral prismatic or elongate crystals ranging from 1mm to 1cm.

Medium altered biotite granite contains sufficient kaolinite to be washed by the monitors as a source of china clay. This material is distinct from the first stage of alteration by its weaker consistency and lower resistance to mechanical impact (e.g. by a hammer).

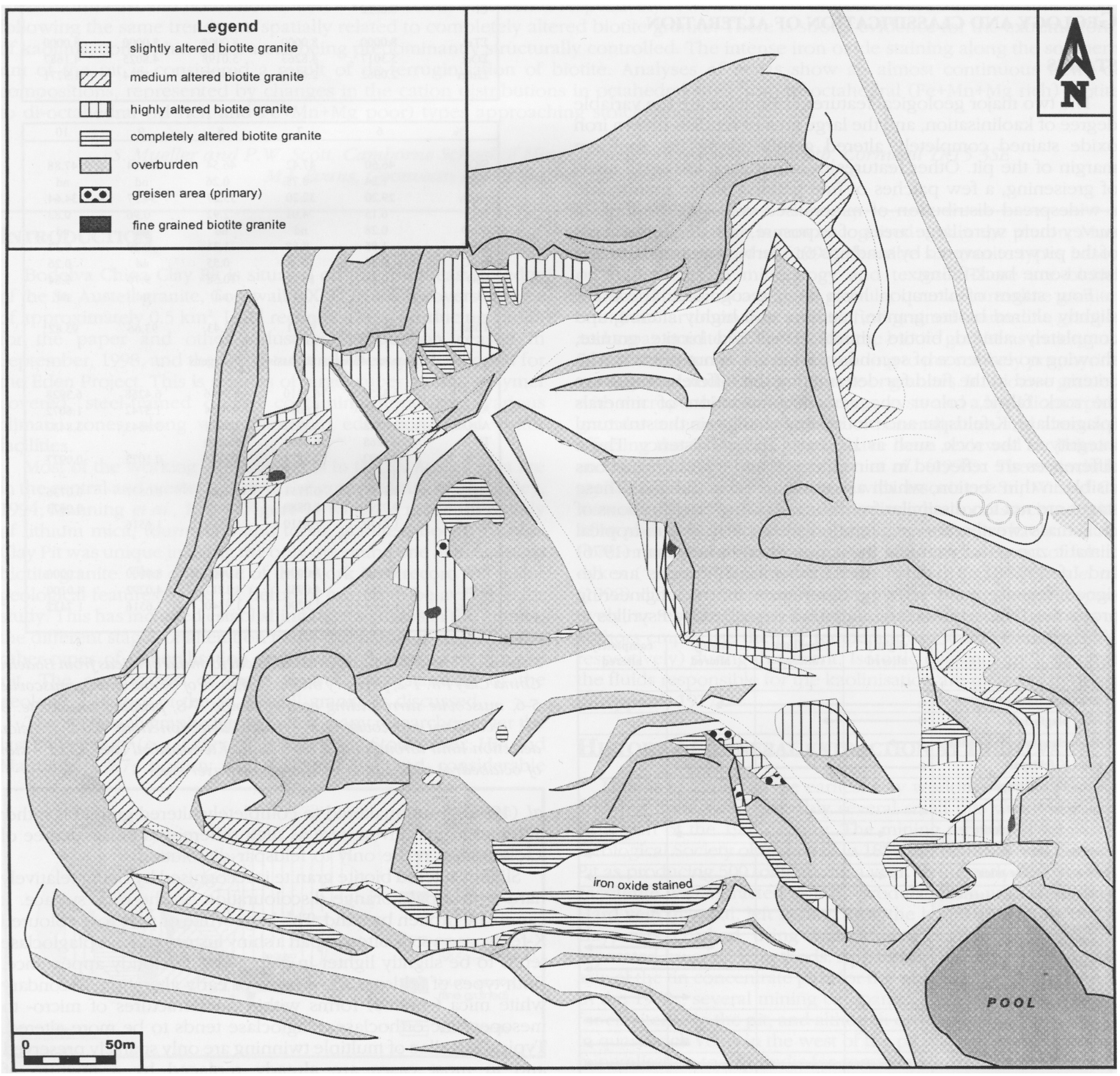

Figure 3. *Distribution of granite alteration stages throughout the pit, together with small patches of primary greisen and fine grained biotite granite.*

The rock strength is appreciably reduced and the rock can be broken by hand. The K-feldspar crystals tend to be more fractured and brittle and generally have lost their shiny lustre. Some of the smaller to medium sized (1-3 cm) feldspar crystals and in particular plagioclase, are covered with a thin very pale greenish coating. On a microscopic scale the advanced grade of alteration is indicated by the complete absence of visible multiple twinning within the plagioclase and the increased amount of secondary white mica within K-rich feldspars. Together with fine grained kaolinite, sometimes forming curled stacks, secondary mica forms a mixture which is pseudomorphing the feldspars. However, the grain boundaries between the decomposed feldspars remain, and the igneous texture is preserved. The de-ferruginisation of brown mica has further increased. In addition, small opaque iron-oxide minerals, varying in size from <10-100µm, occur along basal cleavage planes of altered brown mica.

Highly altered biotite granite is markedly softer than the less altered types. In dry conditions the rock disintegrates very easily. When wet, it can be deformed easily between the fingers. Although the granitic texture is generally preserved, the extent of mineral alteration has led to the nearly complete destruction of plagioclase and considerable decomposition of K-feldspar. Most of the K-feldspar appears virtually isotropic in thin section, being pseudomorphed by a kaolinite and sericite mixture. Curled stacks of kaolinite are common within a fine grained clay-rich matrix. Larger micas tend to be green-grey in colour. Expansion of micas has occurred giving a more wavy rather than platy appearance. Another characteristic feature of highly altered biotite granite is the presence of nodules of iron oxide, referred to by the clay workers as 'paint bombs' or 'red ink bombs'. These concretions, usually of lensoid shape, consist of several layers of either dark reddish-brown or beige-brown cryptocrystalline haematite and limonite/goethite. Each layer is just a few millimetres thick. Some of the nodules reach 15 cm in diameter, the majority however tends to be slightly smaller (5-10 cm). Bristow and Exley (1994) point out that nodules of this type may have been originally composed of sulphides. Some of the quartz grains within highly altered biotite granite show signs of mechanical breakdown. Their shape is predominantly angular compared to quartz grains present in slightly to medium altered granite. Furthermore, the increase in microfractures and cracks running through these grains suggest that they have been subjected to stress.

In the completely altered biotite granite the igneous texture which largely remained in the highly altered biotite granite, is completely destroyed. The rock is extremely soft. It is also variably stained from dark-purple, via ochre/orange to pale yellow by haematite and other hydrous iron oxides, although some remains bright white. There are no feldspar or brown mica relics. Large curled stacks of secondary white mica, mixed with kaolinite (up to 150 µm) (Figure 2) occur along with a very fine grained matrix of kaolinite and sericite. Angular broken quartz grains and subhedral to anhedral tourmaline are embedded within the matrix.

DISTRIBUTION OF ALTERATION

The general distribution of the various alteration stages is much as would be expected, extraction having been concentrated on the more highly altered material of the central parts of the pit (Figure 3). The slightly and medium altered material tends to be situated around the peripheral areas, except in the most southern part of the pit, where mainly highly and completely altered granite is found. However, much of the latter is very stained with iron oxides, making it of no value to the clay producer. The very soft completely altered biotite granite is spatially confined within two narrow (50-100m wide) zones. One is striking north-north-west — south-south-east, the other follows a west-south-west — east-north-east trend. Mostly the contacts between individual stages of alteration are fairly sharp and in places spatially related to single quartz-tourmaline or other veins.

However, in some areas the variation in alteration is on quite a small scale, the detail not being possible to show in Figure 3. A few small areas of fine grained biotite granite occur. Each rarely exceeds more than a few metres in diameter. In general they are characterised by the similar alteration to the surrounding coarse grained variant.

A few irregular shaped greisen bodies, a few metres across, also occur. They are made up of white mica, quartz and large aggregates of tourmaline needles, and are distinct from the granite host rock by their greater rock strength and greenish/grey colour. One greisen body is cut by several small medium to highly kaolinised aplite dykes. This greisened material appears to have been extremely resistant to the process of kaolinisation.

MINERAL VEINS AND DYKES

Several types of veins containing varying assemblages of quartz, tourmaline and other minerals occur. Stereograms summarising the overall orientations of each type are shown in Figure 4.

Greisen bordered quartz-tourmaline veins are the commonest type and are present in almost every part of the pit. In general these veins are composite, consisting of a 0.5-2 cm quartz vein, often filled in its centre or bordered with thin (few mm thick) tourmaline veins, sometimes containing cassiterite, and an area extending symmetrically on both sides of 5-10 cm of greisen. Veins are often in clusters, usually parallel to subparallel steeply dipping between 61-90°. Dip directions towards the north seem to be slightly more common than those to the south. They have a dominant strike direction of east-north-east — west-south-west. The greisen zones are partly kaolinised, unlike the larger areas of greisen referred to above.

Medium to fine grained quartz-tourmaline veins without marginal greisening are characterised by a typical dark-grey to black colour, are up to several decimetres in width and massive in nature. They consist of homogenous euhedral to subhedral quartz and tourmaline. They follow two dominant orientations, north-north-west — south-south-east, with an average strike/dip of 336°/71°, and east-north-east — west-south-west (071°/73°). The latter strikes more or less parallel to the vast majority of greisen bordered quartz-tourmaline veins. However, there is a greater variety of orientations and lower dipping angles (< 60°) are more frequent in these veins. There seems to be a relationship between some of these veins and the completely and highly altered biotite granite. In an area along the south-eastern part of the pit, these veins are bordering an approximately 15 m wide zone of completely altered biotite granite on both sides. Due to their massive nature these quartz-tourmaline veins might have forced any circulating fluids to be restricted within a confined space and therefore increased the effect of alteration, thus contributing to the complete kaolinisation of the adjacent granitic material.

Quartz-haematite veins are widespread in the china clay pit mainly within the highly and completely altered biotite granite facies. Their thickness ranges from a few centimetres up to decimetres. The haematite forms an iron oxide stain on the quartz, resulting in the typical brown or ochre colouration. Individual quartz crystals can grow up to several centimetres in length and quite often exhibit typical hexagonal pyramidal terminations. In few places there is obvious brecciation within the veins. Stereoplots of the quartz-haematite veins show trends which are similar to those followed by the major striking directions of massive quartz-tourmaline veins.

Within slightly, medium and highly altered biotite granite a network of very thin (a few millimetres at most in width) tourmaline veins are found. Figure 4d reports only a small fraction of the total number. Their strike directions are much more varied and they range from nearly horizontal to almost vertical. In general these thin tourmaline veins cross-cut all other veins, suggesting they have formed at a rather late stage of the intrusion history.

There are a few places in the south-eastern part of the pit, mainly within slightly to medium altered biotite granite, where bright green

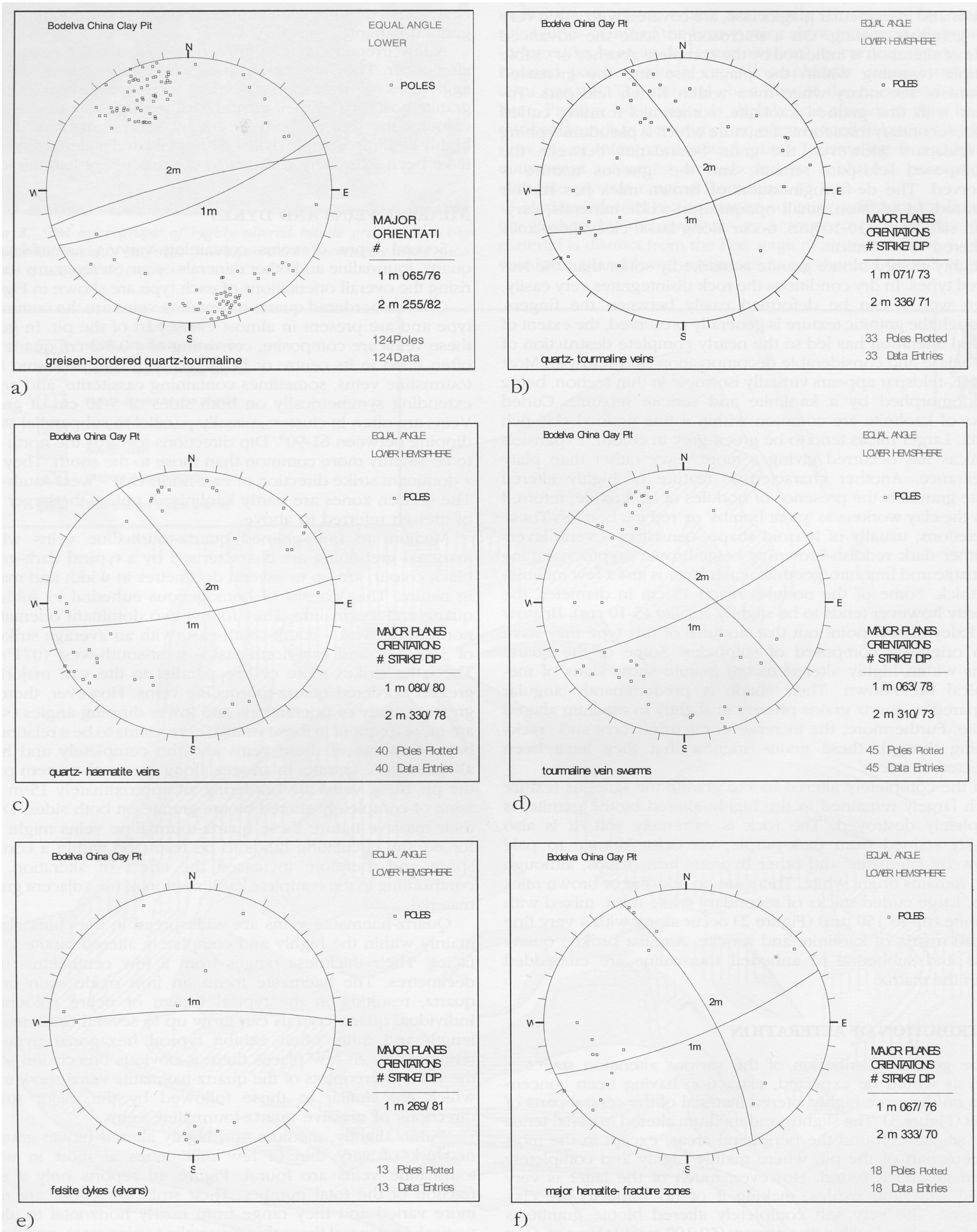

Figure 4. *Stereograms showing the general orientation of various types of mineralised veins, dykes and fracture zones.*

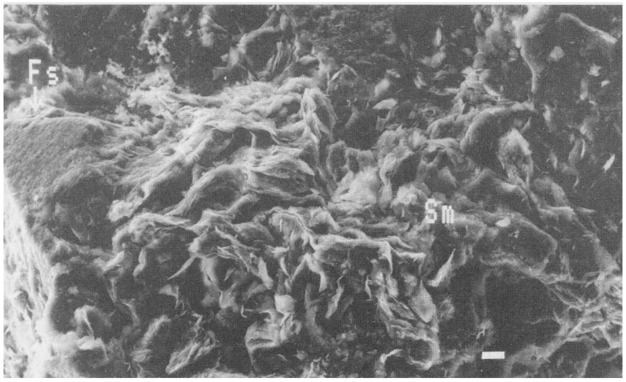

Figure 5. SEM micrograph showing the close relationship between sodium-plagioclase (Fs) alteration and smectite (Sm) formation. The sample is taken from one of the smectite veins. Typical swelling-related features in form of curled edges and folds occur. Scale bar = 10 µm.

coloured smectite (montmorillonite) is concentrated on joint surfaces and within small (2-5 mm) veins. However, two isolated veins of greater thickness (2-3 cm) were found as well. Scanning electron micrographs of this material show characteristic wavy textures with curled edges and folds (Figure 5).

Small and discontinuous pale coloured fine grained felsite dykes (elvans) occur throughout the pit. They range in width from 5 cm up to several decimetres and often vary in thickness along length. The mineral composition of elvans is distinct from the mineral assemblage within the medium to coarse grained host rock. Feldspars rarely exceed 1 cm and the fine grained matrix tends to be much more quartz rich than the granite. Small white mica ($\leq$ 1 mm) flakes and tourmaline needles also occur. Biotite is absent. The tourmaline sometimes forms high concentrations giving the dyke a much more mafic appearance. They commonly have an east-west orientation, although other directions, sometimes with low angles of dip are also represented. The dykes are variably kaolinised to a similar extent to the adjacent granite.

MAJOR HAEMATITE FRACTURE ZONES

There are two major sets of fracture zones cutting through Bodelva China Clay Pit. They are entirely spatially related to completely altered biotite granite and represent areas of weakness

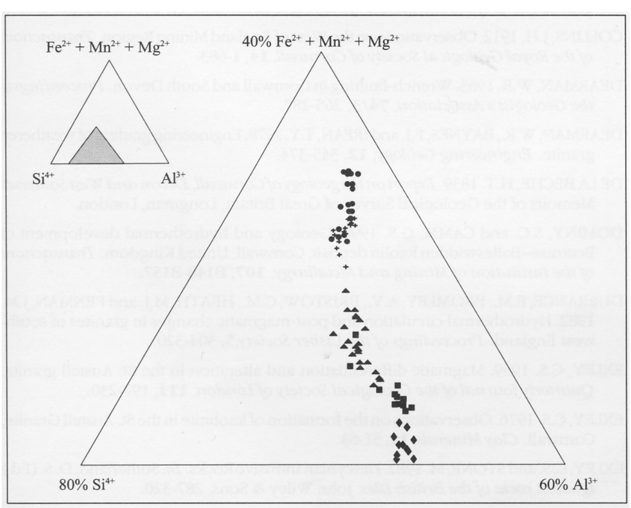

Figure 6. Triangular plot of cation ratios of $Fe^{2+} + Mn^{2+} + M^{g2+}$ Ala^{3+} and Si^{4+} for mica analyses. Unaltered primary biotite (0), biotite cores with outer part altered to muscovite (✚), primary muscovite (■), muscovite surrounding core of biotite (◆) and secondary muscovite associated with kaolinite (●).

Although no evidence for displacement along these fracture or faulting zones is found, several features strongly suggest that in these zones the biotite granite has responded to changes in the overall stress regime, and lateral movement has occurred at some stage after the emplacement of the granite. This is supported by various lines of evidence. There is a general loss of igneous texture in the completely kaolinised granite within these fracture zones. There is a high abundance of angular broken quartz grains, which are distinctly different from those in less altered material. There are vein-like clays with thicknesses of several centimetres to 1-2 dm, and colours ranging from beige-brown to grey-green. In the literature this material is referred to as "fault-gouge" or "flukan" and the faulting systems which they derived from as cross-courses and cross-flukans respectively (Dearman, 1963). Medium to coarse grained quartz is virtually absent within those clays. Instead there is an increase of very fine grained quartz fragments. There is brecciation associated with the quartz-haematite veins embedded in or bordering these zones.

Two main strike orientations for these fracture zones are found (Figure 4f). One is north-north-west — south-south-east trending and is mainly exposed on the northern edge of the pit. It possibly continues across the pit to the pool shown on the map (Figure 3). Evidence for the second orientation is mainly found within the heavily iron oxide stained area along the southern rim of the pit and follows a west-south-west — east-north-east trend. This orientation pattern is consistent with the general direction of the mineral veins present throughout the St. Austell district (De la Beche 1839, p.303, fig. 47). The north-north-west — south-south-east set, which seems to be the more common direction, may be equivalent to that referred to by Collins (1912): "The St. Austell mining district, is traversed by many cross-courses running generally a few degrees W. of N. ". It may be related to the Great Cross Course, which is shown passing close to Bodelva and through St. Blazey to the south (Ussher, 1907). The Fal Valley lineaments exposed within Wheal Remfry China Clay Pit and a haematite rich vein in Rostowrack pit, both in the western lobe of the St. Austell granite complex have similar orientations. In the Bodelva area however, the second principal direction, which follows a west-south-west — east-north-east trend, seems to be the predominant one. The area affected by fracturing in this direction is at least twice as large as in the other orientation and there is more intense iron oxide staining accompanying the intense kaolinisation of the granite. Major fracture intersections of this type may have a significant control on the distribution of kaolinisation in the St. Austell granite. Similar cross course intersections are associated with the china clay pits in the Bodmin Moor granite (Selwood *et al.,* 1998).

MINERAL CHEMISTRY OF THE MICAS

There is petrographic evidence of the alteration of primary biotite to a white mica (de-ferruginisation). In addition both primary and secondary muscovite (referred to as sericite above) also occur. The latter is commonly intergrown with kaolinite to form stacks.

The mineral chemistry of each of the different types of mica in the slightly, medium and highly altered granite has been determined by electron microprobe analysis using a JEOL 840 scanning electron microscope and Oxford Instruments Link AN1000 energy dispersive spectrometer. The analysis quality was assessed using the criteria given in Scott *et al.* (1998). Detection limits are as follows: SiO_2, 0.34%; TiO_2, 0.20%; Al_2O_3, 0.26%; FeO, 0.33%; MnO, 0.21%; MgO, 0.24%; CaO, 0.17%; Na_2O, 0.26%; K_2O, 0.16% Cl, 0.11%. Representative analyses and mineral formulae calculated on the basis of 22 oxygens are given in Table 2. The complete data are plotted in Figures 6 and 7. They show an almost continuous trend of mica compositions, represented by changes in the cation distributions in octahedral sites (Figure 7) from tri-octahedral (Fe+Mn+Mg rich) biotite to di-octahedral (Al rich and Fe+Mn+Mg poor) types approaching stoichiometric muscovite. The tetrahedral site occupancy by Si likewise increases in the muscovites (Figure 6).

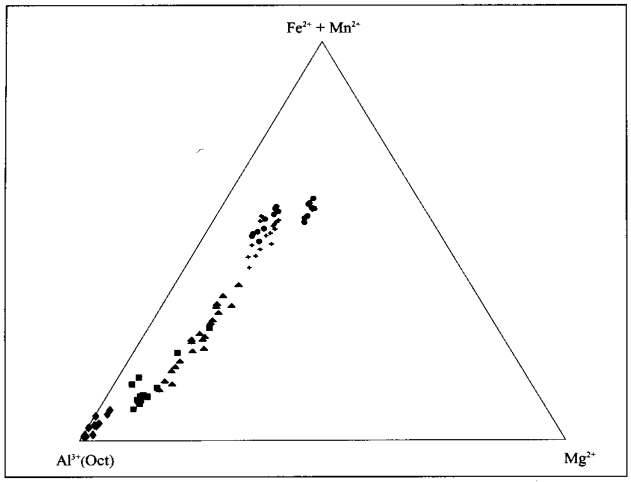

Figure 7. *Cation distributions in octahedral sites ranging from tri-octahedral (Fe+Mn+Mg rich) biotite to di-octahedral (Al rich and Fe+Mn+Mg poor) types approaching stoichiometric muscovite. Symbols as in Figure 6.*

Different rocks appear to have primary biotites with slightly different compositions as there are two populations shown. The biotite cores and relics, now incorporated into white mica crystals, have similar compositions to the primary biotite, and thus are likely also to be unaltered magmatic crystals. Primary muscovite, presumably also from magmatic crystallisation, has some Fe, but contains mostly, but not entirely lower amounts of Fe compared to the muscovite enclosing biotite cores and relics. This indicates that the latter muscovite is derived from the deferruginisation of primary biotite, rather than representing overgrowths of muscovite forming during magmatic crystallisation. The secondary muscovite (sericite) has a composition approaching that of stoichiometric muscovite. Chemically it is different from the primary muscovite in its very low Fe and Mg and absence of Ti.

CONCLUSIONS

Field and petrographic observations have enabled four kaolinisation stages to be distinguished within the biotite granite at Bodelva. The general distribution is such that the less altered material in the form of slightly altered and medium altered granite tends to be situated along the peripheral areas, whereas the highly to completely altered granite is generally more restricted to central parts of the pit. This distribution would be expected, extraction having been preferred in the more profitable highly kaolinised areas.

It is now generally accepted that the kaolinisation of the St. Austell and other granites in Devon and Cornwall is a consequence of supergene processes, whereby from late Mesozoic times, convection cells driven by heat-producing radiogenic elements like U, Th and K, transported meteoric and/or saline surface waters through the granitoids (Durrance *et al.,* 1982; Bristow and Exley, 1994; Bristow, 1998, Dominy and Camm, 1998). Earlier higher temperature hydrothermal mineralisation, which produced the mineral veins, also created microfracturing and phyllic alteration, and increased the overall permeability of the granite making it more susceptible to kaolinisation. At Bodelva, contacts between individual alteration stages are often quite sharp and sometimes are related to a single mineral vein. A direct relationship between the degree of kaolinisation and some mineral veins as shown by Bray and Spooner (1983) and Psyrillos *et al.* (1998) is not shown. In most cases the extent of alteration of the granite is independent of its position in respect to any veining systems. There are also areas of highly or completely altered biotite granite, where relative few veins occur.

A major stress regime has caused further fracturing of the granite in the Bodelva area, forming the two major haematite-rich intersecting fracture zones. Within these zones the alteration is major, resulting in the total destruction and decomposition of all existing feldspars and the formation of completely altered biotite granite. The strict spatial association of completely altered biotite granite in these areas, strongly suggest a predominantly structurally controlled mechanism being responsible for the intensive kaolinisation. The structural data has shown that the north-northwest - south-south-east and west-south-west - east-north-east orientation of the two major haematite fracture zones is consistent with the two main strike directions characterising the vast majority of vein systems in the St. Austell granite. Thus, the formation of these haematite fracture zones is a consequence of an increase in stress rather than a change of the stress direction itself. These intersecting fracture zones within the Bodelva area have also allowed Fe-bearing minerals, deriving from biotite alteration, to be concentrated into confined spaces, namely the fracture system itself, and/or to be carried out of the system entirely. Without these fracture zones the iron oxides released during kaolinisation most probably would have affected a much larger area and the quality of kaolin would have been reduced. Finally, assuming the relatively small number of china clay pits within the biotite-rich eastern part of the St. Austell granite reflects a low degree of kaolinisation of the granite, it may reflect a paucity of other highly permeable fracture zones, similar to those occurring at Bodelva.

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REFERENCES

BRISTOW, C.M. 1998. China Clay. Pp. 167-178. in SELLWOOD, E.B., DURRANCE, E.M. and BRISTOW, C.M. 1998. *The geology of Cornwall.* University of Exeter Press, 298pp.

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 ROBSON, J.L. 1994. Palaeogene basin development in Devon. *Transactions of the Institution of Mining and Metallurgy,* **103,** B163-B174.

COLLINS, J.H. 1912. Observations on the West of England Mining Region. *Transactions of the Royal Geological Society of Cornwall,* **14,** 1-683.

DEARMAN, W.R. 1963. Wrench-faulting in Cornwall and South Devon. *Proceedings of the Geologist's Association,* **74/3,** 265-287.

DEARMAN, W.R., BAYNES, F.J. and IRFAN, T.Y. 1978. Engineering grading of weathered granite. *Engineering Geology,* **12,** 345-374.

DE LA BECHE, H.T. 1839. *Report on the geology of Cornwall, Devon and West Somerset.* Memoirs of the Geological Survey of Great Britain, Longman, London.

DOMINY, S.C. and CAMM, G.S. 1998. Geology and hydrothermal development of Bostraze-Balleswidden kaolin deposit, Cornwall, United Kingdom. *Transactions of the Institution of Mining and Metallurgy,* **107,** B148-B157.

DURRANCE, E.M., BROMLEY, A.V., BRISTOW, C.M., HEATH, M.J. and PENMAN, J.M. 1982. Hydrothermal circulation and post-magmatic changes in granites of southwest England. *Proceedings of the Ussher Society,* **5**, 304-320.

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

EXLEY, C.S. 1976. Observations on the formation of kaolinite in the St. Austell Granite, Cornwall. *Clay Minerals,* **11,** 51-63.

EXLEY, C.S. and STONE, M. 1982. Hercynian Intrusive Rocks. *In:* Sutherland, D. S. (Ed.) *Igneous rocks of the British Isles.* John Wiley & Sons, 287-320.

HILL, P.I. and MANNING, D.A.C. 1987. Multiple intrusions and pervasive hydrothermal alteration in the St. Austell granite, Cornwall. *Proceedings of the Ussher Society,* **6**, 447-453.

HENWOOD, W.J. 1843. On the Metalliferous Deposits of Cornwall and Devon. *Transactions of the Royal Geological Society of Cornwall,* **5,** 1-386.

IRFAN, T.Y. 1981. Mineralogy, fabric properties and classification of weathered granites in Hong Kong. *Quarterly Journal of Engineering Geology,* **29**, 5-35.

MANNING, D.A.C., HILL, P.I. and HOWE, J.H. 1996. Primary lithological variation in the kaolinized St. Austell Granite, Cornwall, *England. Journal of the Geological Society of London,* **153**, 827-838.

PSYRILLOS, A., MANNING, D.A.C. and BURLEY, S.D. 1998. Geochemical constraints on kaolinization in the St. Austell Granite, Cornwall, *England. Journal of the Geological Society of London,* **155**, 829-840.

SCOTT, P.W., PASCOE, R.D. and HART, F.W. 1998. Columbite-tantalite, rutile and other accessory minerals from the St. Austell topaz granite, Cornwall. *Geoscience in southwest England,* **9**, 165-170.

SELWOOD, E.B., THOMAS, J.M., WILLIAMS, B.J., CLAYTON, RE., DURNING, B., SMITH, O. and WARR, L.N. 1998. Geology of the Country around Trevose Head and Camelford. *Memoir of the British Geological Survey,* Sheets 335 and 336 (England and Wales), 1-106.

SHEPPARD, S.M.F. 1977. The Cornubian batholith, south-west England: D/H and $^{18}O/^{16}O$ studies of kaolinite and other alteration minerals. *Journal of the Geological Society of London,* **133**, 573-591.

USSHER, W.A.E. 1907.6 inches to one mile manuscript Geological Map of St. Austell area. Geological Survey of Great Britain.