Mineral Resources
Consultative Committee

Mineral Dossier No 26

China Clay

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Acknowledgements

Metric units are employed throughout this document except where otherwise stated. In most cases
this has necessitated the conversion of originally non-metric data. The units and conversion factors
used are as follows:

millimetres (mm)	= inches × 25.4
metres (m)	= feet × 0.3048
kilometres (km)	= miles × 1.609344
hectares (ha)	= acres × 0.404686
grammes (g)	= troy ounces × 31.1035
kilogrammes (kg)	= pounds × 0.45359237
tonnes (1000 kg)	= long tons × 1.01605
cubic metres (m³)	= cubic feet × 0.028317

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Preface

The Mineral Resources Consultative Committee consisted of
representatives of interested Government Departments, and specialist
advisers. It was set up in 1967 to keep present and future requirements
for minerals under review and to identify problems associated with the
availability, exploitation and use of mineral resources, both inland and
offshore, having regard to competing demands on land use and other
relevant factors.

Widespread and increasing interest in the mineral resources of the United
Kingdom led the Committee to undertake the collation of the factual
information available about those minerals (other than fossil fuels) which
were being worked or which might be worked in this country. The
Committee produced a series of dossiers, each of which was circulated in
draft to the relevant sectors of the minerals industry. They bring together
in a convenient form, in respect of each of the minerals, data which had
previously been scattered and not always readily available. These dossiers
in updated form are now being published for general information.

Summary

China clay, or kaolin as it is internationally known, is a white clay consisting predominantly of kaolinite. The mineral forms the basis of a large extractive industry in the United Kingdom and the deposits of Southwest England are world famous for their high quality. The United Kingdom is, after the USA, the second largest producer of kaolin but the leading world exporter, with over 80 per cent of annual output exported. In 1982 the United Kingdom produced some 2.4 million tonnes of kaolin valued at about £135 million. The deposits are a major mineral resource and, until the advent of North Sea oil, kaolin was the United Kingdom's major mineral export.

Although originally valued for use in whiteware ceramics, kaolin is now used mainly in papermaking (some 80 per cent of United Kingdom output), both for paper coating and paper filling. Subsidiary amounts are used as fillers in paint, rubber and plastics and have a wide range of other uses.

The deposits of Southwest England were formed by the *in situ* alteration of the feldspar component (principally sodic plagioclase) of the Variscan granites, all of which have been worked. Production has, however, centred mainly on the St Austell Granite, which accounts for 75 per cent of production, and the southwestern margin of the Dartmoor Granite (20 per cent). Small quantities are produced on Bodmin Moor and near Land's End.

The kaolinised granite—the clay matrix—consisting principally of quartz, micaceous mineral, feldspar and kaolinite, is hydraulically mined. Kaolinite, occurring mainly in the $<20\ \mu m$ fraction, is recovered principally by wet classification by sedimentation, hydrocycloning and centrifuging. Total clay yields are usually in the range 10 to 15 per cent and thus large quantities of waste are produced, which has a major impact on the environment. Marketable grades are assessed for brightness, particle size distribution, viscosity and, in the case of potting clays, a wide range of ceramic properties.

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Introduction

China clay, or kaolin as it is more widely known internationally, is a commercial clay composed principally of the hydrated aluminosilicate *kaolinite* and exhibiting a marked whiteness in its natural state. The term 'kaolin' is derived from Kaoling (now Gaoling), a village in northeast Jiangxi province in China, near where the white clay was worked for over a thousand years for the manufacture of fine white porcelain. White Chinese porcelain was produced from a refined, white kaolin and china stone or 'petuntse' (a mixture of feldspar and quartz), which acted as the flux. For many years the composition of Chinese porcelain was a closely guarded secret but in the early 18th century the raw materials used in its manufacture were recognised and deposits were sought in Europe. In Britain William Cookworthy (1705-80), a Plymouth chemist, recognised their occurrence in Cornwall, firstly in the Tregonning-Godolphin Granite in 1746 and subsequently in the St Austell Granite (Barton, 1966). Cookworthy finally took out a patent for the manufacture of porcelain from Cornish china clay and china stone in 1768 and, whilst the tin miners had for many years used the clay for refractory purposes, Cookworthy is regarded as 'the father of the Cornish china clay industry'.

The deposits attracted the attention of the Staffordshire potters and until the early 19th century china clay was used almost exclusively in the production of fine ceramics. However, the development of china clay as a filler in papermaking had a far reaching effect on the industry and markedly increased demand for the mineral, particularly during the latter part of the 19th century. Demand increased still further with the introduction of paper coating at the beginning of the 20th century and prior to the First World War some 75 per cent of total output was consumed by the paper industry, a similar proportion to today.

The china clays of Southwest England are world famous both for their high quality and for the size of the deposits, which have yielded some 110 million tonnes of marketable clay since production began in the mid-18th century. The essential constituent of the deposits is the clay mineral kaolinite which was formed by *in situ* alteration of the granite. In Britain it has been customary to refer to these clays as 'china clays'. Elsewhere however, clays composed chiefly of white kaolinite (or related clay minerals) are usually called 'kaolin', but the two terms may be regarded as being synonymous. For convenience and consistency the term 'kaolin' has been used throughout this document.

Kaolin is sometimes defined as 'a clay characterised by a useful content of kaolin minerals'. This definition is unsatisfactory, however, since it

embraces other kaolinite-rich clays, such as ball clays, fireclays and flint clays which exhibit properties and therefore industrial uses very different from those normally associated with kaolin. In particular they lack whiteness, the main attribute of kaolin. A much more satisfactory definition based on Patterson and Murray (1975) is as follows:— 'Kaolin is a clay consisting substantially of pure kaolinite, or related clay minerals, that is either naturally white or can be beneficiated to be white, or nearly white, will fire white, or nearly white, and is amenable to beneficiation to make it suitable for use in whiteware ceramics, paper, rubber, paint and similar uses'.

Kaolinite mineralogy

Most kaolin deposits consist of kaolinite in various degrees of concentration, although other kaolin group minerals may also be present. The kaolin group of clay minerals, comprising kaolinite, halloysite and the two polymorphs, dickite and nacrite, belong to the phyllosilicate family of rock-forming minerals and exhibit well-defined layer structures. The structures of layer silicates have been comprehensively reviewed by Bailey (1980). The kaolin group minerals consist of a two sheet (1:1) layer structure comprising one tetrahedral sheet and one octahedral sheet. The former is so named because of the tetrahedral configuration by which oxygen atoms surround each silicon cation. Individual tetrahedra $(SiO_4)^{4-}$ are linked by sharing three basal oxygens with adjacent tetrahedra to give a two-dimensional sheet with the composition $(Si_4O_{10})^{4-}$. Similarly, in the octahedral sheet, aluminium is surrounded by six hydroxyl groups in an octahedral configuration, individual octahedra being linked laterally by sharing octahedral edges. The smallest structural unit contains three octahedra and in the kaolin group of clay minerals only two of these are occupied by aluminium the third being vacant. The sheet is therefore classified as dioctahedral. (Two sheet (1:1) layer
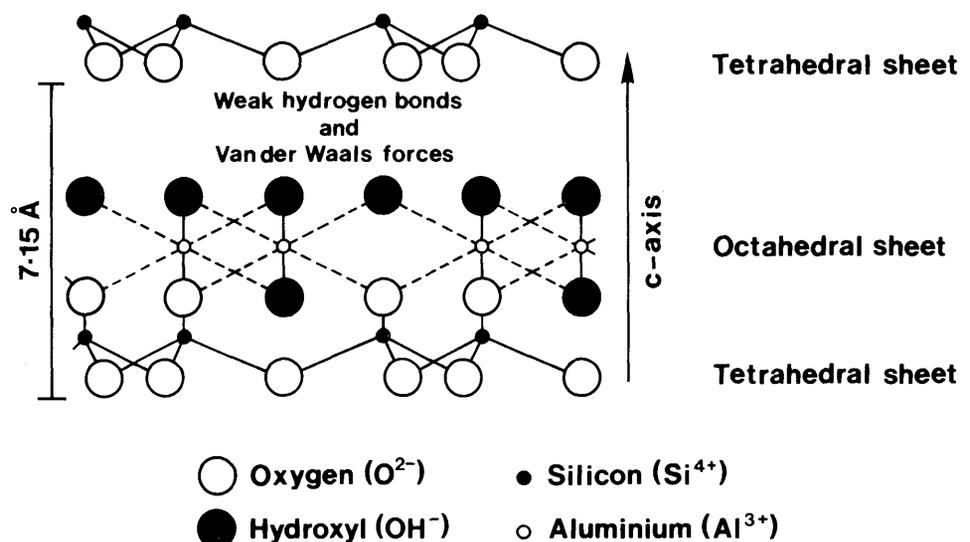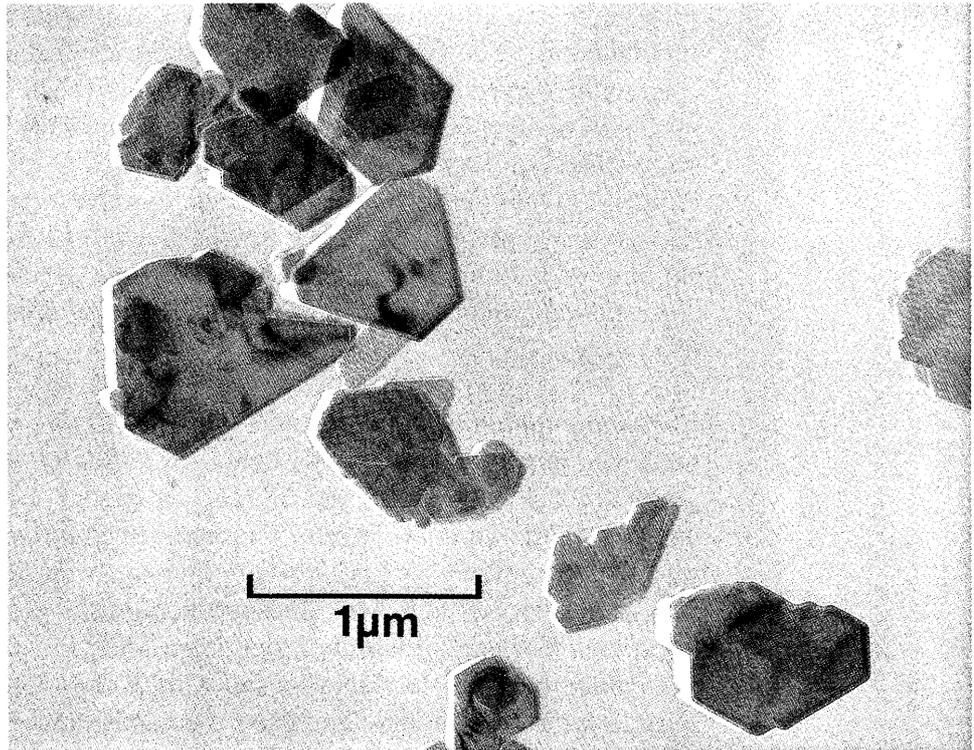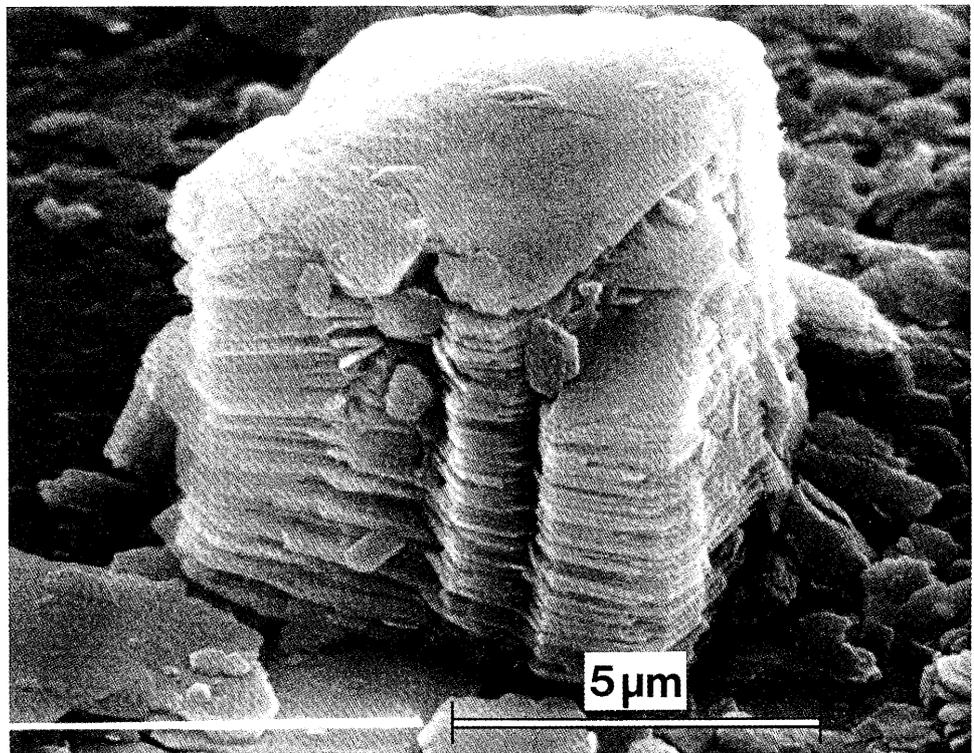

Fig 1 Crystal structure of kaolinite

Fig 2 Transmission electron micrograph of kaolinite crystals
(By Courtesy of English Clays Lovering Pochin & Co Ltd)

Fig 3 Scanning electron micrograph of a kaolinite crystal
(By Courtesy of English Clays Lovering Pochin & Co Ltd)

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silicates, where all the octahedra are occupied by cations, are described as trioctahedral). The junction between the tetrahedral and octahedral sheets consists of shared apical oxygens (from the tetrahedral sheet) and unshared hydroxyl groups (from the octahedral sheet), which occur at the same structural level (Fig 1). All the kaolin group minerals exhibit this basic 1:1 layer structure, the difference between them being in the way the layers are vertically stacked along the c-axis to form the crystal. In the case of kaolinite the basal spacing between corresponding layers of atoms in adjacent layers, including the interlayer space, is 7.15 Å (0.715 nm).

Unlike the ionic bonds which bind the tetrahedral and octahedral sheets, weak van der Waals forces and hydrogen bonds between the hydroxyl groups of the octahedral sheet and the oxygen of the adjacent tetrahedral sheet bond the kaolinite layers. The number of layers that can be stacked together along the c-axis is therefore limited, often resulting in flat, hexagonal platy or lamellar crystals which, in the case of the deposits of Southwest England, generally range from 5 μm to 0.1 μm in diameter and have mean diameter to thickness ratios of 30:1 to 10:1 (Fig 2). Vermicular stacks of lamellae along the c-axis may, however, achieve lengths of over 10 μm. (Fig 3).

The 1:1 layer structure exhibited by the kaolin group is electrically neutral and the minerals may have chemical compositions close to the ideal formula of $Al_2Si_2O_5(OH)_4$, corresponding to a theoretical composition of 39.5 per cent Al_2O_3; 46.55 per cent SiO_2, and 13.95 per cent H_2O. Some replacement of Al^{3+} by Fe^{3+} may occur, but substitution is rare. Unlike most other clay minerals, therefore, the layer charge does not need neutralizing by interlayer materials (mainly cations), which accounts for the very low cation-exchange capacity of kaolinite. The polymorphs dickite and nacrite differ from kaolinite in the stacking of the layers, with unit repeats along the c-axis of 14Å and 42Å respectively, and in the position of aluminium in the octahedral sheet. They are also much rarer than kaolinite, although sometimes present in commercial kaolin deposits. Halloysite shows a variety of fibrous, tubular and curved forms, based on a rolled layer structure. Water molecules occur in the interlayer spacing and the separation of the kaolinite layers is increased from 7.15Å to about 10Å (hydrated halloysite). The water molecules are, however, easily removed at temperatures as low as 60°C and the dehydrated form (halloysite -7Å) is not easily rehydrated. Kaolin deposits containing halloysite are commercially exploited in some parts of the world.

Kaolinite may exhibit various kinds and degrees of disorder resulting from either the geological conditions of formation, transport and deposition, or subsequent mechanical treatment such as fine grinding and delamination due to shear pressure. The deposits of Southwest England contain well-ordered kaolinite which typically exhibits relatively well-formed, coarse-grained, hexagonal lamellar habits. In contrast, many

sedimentary kaolinitic clays are poorly ordered, showing a range of disorder due principally to random displacements of the unit layers parallel to the b-axis and also due to substitution of Fe^{3+} for Al^{3+} in the lattice. They are commonly referred to as 'b-axis disordered kaolinites' and in the United Kingdom are exemplified by ball clays and fireclays. The degree of ordering may be distinguished by X-ray diffraction (XRD) and infra-red spectroscopy. An empirical method for determining a 'crystallinity index' from X-ray diffractograms has been developed by Hinckley (1963) in which perfectly ordered kaolinite has a value of 2 and completely disordered kaolinite a value of 0. Typical values for English kaolins are 1.0 to 1.3, whilst for ball clays indices are generally less than 0.4. Some ball clays in the Bovey Basin exhibit crystallinity indices of up to 0.9 and clearly were derived from the re-working of primary kaolin deposits (Vincent, 1982). However, some well-crystallised kaolinites, as shown by electron micrographs, may give poor crystallinity indices solely because of their fine particle size. Interpretation of crystallinity from XRD patterns must therefore be undertaken with care. Disordered kaolinites have markedly smaller crystals than well-ordered varieties and, as a result, exhibit much higher plasticities and strengths. In addition isomorphous substitution results in an electrical imbalance in the structure, and thus base-exchange capacity generally increases with degree of disorder. However, substitution is rare in well-ordered kaolinites so that they generally have low iron values and consequently a high whiteness and brightness, both in the natural and fired state. Depending on their origin and mode of occurrence therefore, kaolinitic clays may exhibit markedly different properties and thus have very different industrial applications.

Classification of kaolin deposits

Kaolin deposits are widely distributed throughout the world and new deposits continue to be found. However, deposits of a size and quality comparable to those in Southwest England are rare and the availability of a full range of grades from a single deposit is exceptional. Of particular note, however, are the very extensive sedimentary deposits in Georgia and South Carolina in the southeastern USA which support the world's largest production by far, and the more recently discovered kaolin deposits in the Amazon Basin in Brazil.

Kaolin deposits may conveniently be classified as either primary or sedimentary. Primary, or residual, deposits were formed by the *in situ* alteration of the parent rock, which may have been igneous, metamorphic or sedimentary in origin, by volcanic, hydrothermal or weathering processes, either separately or possibly in combination. In contrast sedimentary, or secondary, kaolins have been derived from the erosion of pre-existing deposits and the subsequent transport and deposition of the clay in a non-marine environment (Bristow, 1980). The deposits of Southwest England and in Georgia and South Carolina are regarded as the type localities for primary and sedimentary deposits, respectively.

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Lateritic weathering is a major process in kaolinite formation. Some kaolin deposits appear to have formed by the alteration *in situ* of aluminous sediments, for example arkosic sandstones. Often such deposits have been subject to reworking to give true sedimentary kaolins. However, where no reworking has taken place the distinction between primary and sedimentary kaolins is obscure, although convention appears to consider them as sedimentary deposits.

Sedimentary kaolins may however range from comparatively high purity, kaolinite-rich sediments of variable particle size, typified by the Georgia deposits, to kaolinitic sands containing perhaps less than 20 per cent clay. In addition other factors, such as brightness, particle size, kaolinite crystallinity and associated minerals, have a marked effect on the properties of the clay and thus its industrial applications. A continuous series from sedimentary kaolins to plastic ball clays has therefore been defined by Bristow (1979). However, natural brightness is the main parameter for distinguishing sedimentary kaolins from other kaolinitic sediments.

Resources

The host rocks to the kaolin deposits of Southwest England are Variscan granites intruded into an intensely folded, weakly metamorphosed, thick sedimentary succession comprising dark-coloured shales (locally called 'killas'), siltstones, sandstones, greywackes, scattered limestones and volcanics of Lower Devonian to Upper Carboniferous age. Gravity (Bott *et al,* 1958) and seismic evidence indicate that the granites are connected at depth and represent high-level plutons of the elongate Cornubian Granite batholith which stretches over 200 km from the Scilly Isles to Dartmoor and is up to 50 km wide. The polymetallic mineralisation of Southwest England is spatially associated with the granite and most of the epigenetic mineral deposits lie close to the roof of the batholith. All the granites and certain 'elvans' (dyke or sill-like quartz porphyries) have been kaolinised to some extent and the major intrusions—Dartmoor, Bodmin Moor, St Austell, Carnmenellis and Land's End granites, excepting that comprising the Scilly Isles, have been worked for kaolin. The smaller intrusions such as those of Tregonning-Godolphin, Carn Marth and Hingston Down have also been worked to a minor extent. Major production has, however, been confined to the western and central parts of the St Austell Granite, which currently accounts for some 75 per cent of total production, and the southwestern margin of the Dartmoor Granite, which accounts for a further 20 per cent. In addition a relatively small amount is produced on Bodmin Moor and at Bostraze on the Land's End Granite.

The principal rock types recognised in the Variscan granites of Southwest England are (Exley and Stone, 1964; Hawkes and Dangerfield, 1978):

1. Coarse-grained, biotite granite
2. Medium-grained, lithium-mica granite
3. Fine-grained, biotite granite

Coarse-grained, biotite granite containing large K-feldspar crystals (megacrysts) up to 170 mm in length, comprises over 90 per cent of the main plutons. Apart from the lithium-rich varieties characterised by the presence of a pale-brown lithium-bearing mica (sometimes called 'lithionite'), the granites are all composed of some two-thirds K-feldspar and sodic plagioclase and about 30 per cent quartz with the balance comprising variable amounts of biotite and accessory minerals which commonly include tourmaline—the most conspicuous accessory, muscovite, chlorite, monazite, apatite, zircon, and topaz (Hawkes, 1982).

The British Geological Survey has recently completed mapping the granites of Southwest England and the following classification has been proposed principally on textural grounds (Hawkes and Dangerfield, 1978; Dangerfield and Hawkes, 1981).

Coarse granite	{ megacrystic types
	{ smaller megacryst variant
Medium, lithium-mica granite	non-megacrystic
Medium granite	{ with few megacrysts
	{ megacrysts very rare
Fine granite	{ megacryst-rich types
	{ megacryst-poor types

The coarse-grained granites, which have a minimum mean groundmass grain size of 2-3 mm, are characterised by large K-feldspar megacrysts ranging up to 170 mm in length and comprising from 1 to 30 per cent of the rock. The smaller megacryst variant is distinguished on the size of the feldspar megacrysts, which range generally up to 40 mm in length (mean 20 mm). All the coarse granite variants show gradational relationships to one another. The K-feldspar megacrysts, which are now orthoclase perthites containing in some cases domains of microcline, formed originally by solid-state replacement of plagioclase (Hawkes, 1982).

In contrast, the lithium-mica granite lacks megacrysts but displays an even, medium-grained texture (1-2 mm) and contains a pale lithium-bearing mica instead of the more widespread dark brown biotite. The identity of this species is still in doubt but it appears to range in composition between zinnwaldite and lepidolite. In addition, the plagioclase is more albitic in composition and there is a relative abundance of topaz. The fine-grained granites, which exhibit a minimum mean groundmass grain size in the range 0.06 mm to 0.6 mm, have been divided into biotite-rich types, containing numerous megacrysts of feldspar, quartz and biotite, and biotite-poor varieties in which megacrysts are rare or locally absent. A further granite with a medium-grained groundmass (1-2 mm) with very few or rare megacrysts has also been distinguished (Dangerfield and Hawkes, 1981).

The distribution of the principal granite types is shown on Fig 4. Coarse-grained, megacrystic varieties occur in the Dartmoor, St Austell and Land's End granites, whilst the small megacryst variant is mainly

Fig 4 Distribution of the principal granite types of Southwest England. (After Dangerfield and Hawkes, 1981).

confined to the Bodmin Moor, Carnmenellis and Isles of Scilly plutons. The lithium-mica granite is confined to the central-western parts of the St Austell Granite, with a much smaller body occurring eastsoutheast of Hensbarrow Beacon, and to most of the Tregonning-Godolphin Granite. Lithium-mica also occurs in the Meldon Aplite which forms a 3.5 km long dyke intrusive into country rocks northwest of the Dartmoor pluton, although there is no associated kaolinisation. Fine granite is more irregularly distributed but, in addition to the larger outcrops, numerous small isolated pods, horizontal, inclined and vertical sheets, and irregular masses also occur.

Kaolinisation

The granites of Southwest England have been affected by post-emplacement alteration of three main types; tourmalinisation, greisenisation and kaolinisation. Greisen-bordered, quartz-tourmaline veins, which only locally carry cassiterite and wolframite, are a conspicuous feature in the kaolin pits because of their colour and harder nature compared with the surrounding kaolinised granite. The quartz veins, which are associated with joints, are each typically bordered by a band of tourmalinisation in which feldspar and mica and, to a limited extent, quartz have been replaced by tourmaline, and a greisened zone in which feldspar has been altered to mica and quartz with minor accessory minerals such as tourmaline, topaz and fluorite. The veins are usually sub-vertical and generally strike east-west or eastnortheast- westsouthwest.

Fig 5 Extent of kaolinisation in the granites of Southwest England

Vein thicknesses are highly variable, ranging from a few millimetres up to 30 cm, although occasionally they may be thicker. The quartz and quartz-tourmaline veins may occur as swarms or sheeted vein complexes with which intense kaolinisation is spatially associated. However, not all kaolinised zones are associated with vein systems. All the granite types have been affected by kaolinisation, the extent of which is shown on Fig 5.

Kaolinite is derived from the decomposition of feldspar, especially sodic plagioclase, and an inverse relationship exists between the presence of albite and kaolinite, secondary mica being an important intermediate phase (Exley, 1959). K-feldspar megacrysts a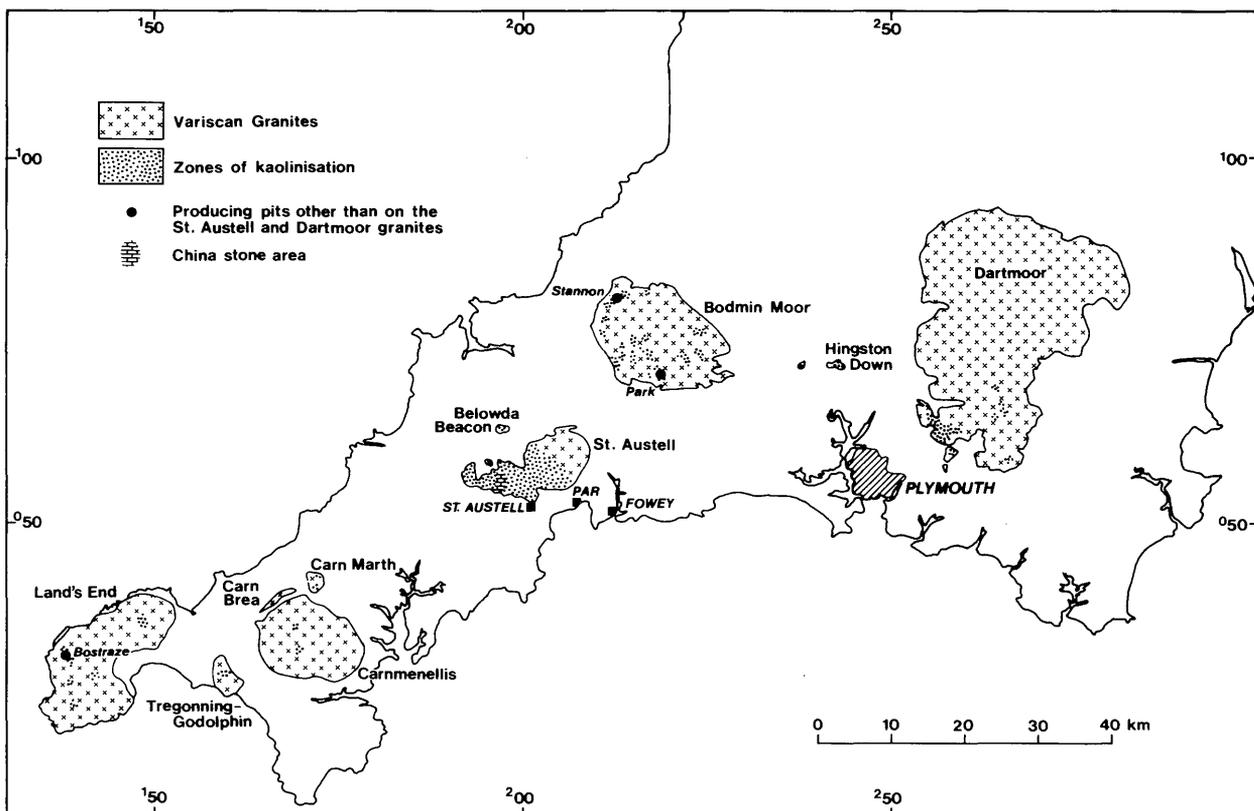re less readily altered except under extreme conditions. Smectite is also an intermediate product between plagioclase and kaolinite and is found in very narrow zones a few centimetres thick at the kaolinisation 'front' (Exley, 1964; 1976). The formation of kaolinite therefore is dependent on the destruction of secondary mica and smectite. The presence of smectite, even in very small amounts, is commercially very important since it may have a serious detrimental effect on the rheological properties of the kaolin, of particular importance where the clay is used in paper coating. During kaolinisation quartz and tourmaline remain largely unchanged, although the former exhibits corrosion, whilst mica may be either unaltered or recrystallised in a finer-grained form. Major geochemical changes are associated with kaolinisation with the removal of alkalies, alkaline earths and silica and resulting in a volume decrease of about 30 per cent (Exley, 1959; Bray and Spooner, 1983). Of major commercial significance for the production of high brightness clays is the removal of iron.

Kaolinisation is spatially related to the joint and vein systems in the granites, which are thought to have formed the channelways through which the kaolinising fluids moved (Exley, 1959). The intensity of kaolinisation diminishes rapidly away from them, the transition from kaolinised granite to relatively unaltered rock occurring over a metre or so. In addition, the crystallinity of kaolinite also increases towards the major quartz-tourmaline veins and joints (Exley and Stone, 1964). However, by no means all kaolinised granite is associated with quartz-tourmaline veins.

The kaolinised zones are funnel or trough-like in form, narrowing downwards (Fig 6). Kaolinisation may, however, extend to considerable depths, the 'stems' of funnels having been intersected by drilling as much as 300 m below the surface. This simplified morphology is, however, complicated by the coalescence of individual funnels to give more extensive areas of kaolinisation, sometimes of irregular shape, extending laterally for over 2,000 m. There is, therefore, no clear relationship between the shapes of the kaolinised areas and main vein directions (Bristow, 1969). Some of the kaolinised zones dip steeply so that kaolinisation may occur beneath relatively unaltered granite.

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Fig 6   Idealised cross section of a kaolin pit (After Bristow, 1969).

Kaolinised granite, known as the 'clay matrix', consists of a friable aggregate composed principally of quartz, mica, K-feldspar and kaolinite with additionally a number of accessory minerals, the most important of which is tourmaline. Kaolinite occurs mainly within the <20 μm fraction, allowing its ready separation from the other coarser components of the clay matrix. The kaolinite content of the matrix (or more precisely the marketable clay content) is variable and, whilst it may exceptionally be as high as 40 per cent, a content of 15 to 25 per cent is more typical. However, clay yield from a given block of ground is not solely a function of the kaolin content of the clay matrix. The presence of quartz-tourmaline veins, iron-stained and incipiently kaolinised granite intimately associated with the areas of kaolinisation, may significantly reduce total yield. Filler grade yields are thus overall some 10 to 15 per cent, whilst yields of finer-grained paper coating grades are somewhat lower. Minimum economic clay yields are currently about 9 per cent, although in smaller operations higher yields would generally be required.

The high porosity (and thus higher moisture content) and lower density (saturated bulk density 2.0 to 2.2 g cm^{-3}) of kaolinised granite compared with the unaltered rock means that low resistivity and gravity values correlate well with areas of kaolinisation. In Cornwall and Devon, however, the main areas of kaolinisation are now well established and core drilling is, therefore, essential for clay quality evaluation and reserve assessment. The main properties assessed are clay yield (also providing information on the quantity of waste for disposal, essential for long term planning) and brightness, although examination of a wide range of other criteria such as viscosity and numerous ceramic properties is necessary to evaluate the suitability of the clays for particular applications. Borehole spacing is usually on a 100 m grid, although this may be reduced to 40 to

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60 m if greater detail is required. Geostatistical and computer techniques have been adopted to assist in reserve calculation. Information on the distribution of specific clays and their individual properties can be rapidly recalled, allowing not only the continuous evaluation of reserves, but also greatly assisting mine planning by predicting quality in advance of working and thus the need for blending to give consistency.

The quality of the deposits may vary significantly. The effect of smectite has already been mentioned but iron content has the most important influence on commercial value, significantly affecting the natural and fired brightness of the clay. Iron contamination may take the form of a yellowish staining due to the presence of hydrated iron oxides but in some areas locally severe red staining due to hematite renders the clay matrix unworkable. The presence of fine-grained iron-bearing micas may also be serious, particularly if the clay is used for ceramic applications where a good fired colour is of paramount importance.

Despite a long history of production, the widespread nature and depth of kaolinisation, particularly in the St Austell Granite and also on the southwestern margin of the Dartmoor Granite, will ensure continuing extraction over a long period. No reserve figures are published but current long term plans allow for continuous production for at least 50 years.

Origin

The controversy over the precise origin of the kaolinisation in Southwest England has a long history. A hydrothermal origin was originally advocated and until recently this has been the generally accepted view (Collins, 1878; 1909; Exley, 1959; Bristow, 1969). However, early suggestions (Hickling, 1908; Coon, 1911) that the kaolinisation was related to supergene processes (near-surface weathering) have more recently been revived (Konta, 1969; Sheppard, 1977). The evidence for the origin of the kaolinisation has been comprehensively reviewed by Bristow (1977) and the main points are summarised below.

The shape and depth of the kaolinised zones is regarded as the principal evidence for a hydrothermal origin for the deposits and it is difficult to envisage how they could have formed by weathering alone. Whilst kaolinised granite has not, as yet, been conclusively found beneath a continuous sheet of unkaolinised granite, the presence of kaolinised granite beneath a thick cover of unaltered 'killas' is difficult to explain other than by 'damming back' of hydrothermal fluids beneath an impermeable cover. The field evidence, therefore, points to a hydrothermal origin for the kaolin deposits.

Quartz-tourmaline veins occur in many of the kaolinised zones, although they are neither confined to kaolinised granite nor always present. However, the intensity of kaolinisation and the crystallinity index of the kaolinite has been shown (Exley and Stone, 1964) to increase towards

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major quartz-tourmaline veins, thus implying that they formed the channels along which the kaolinising fluids moved.

The kaolinitic ball clay deposits of Devon and Dorset indicate that humid, tropical to sub-tropical climatic conditions did affect Southwest England during Lower Tertiary times giving rise to intense weathering. Nevertheless the granites are preferentially kaolinised and the 'killas' affected only to a limited extent, whereas lateritic weathering affects virtually all types of rocks. In addition, whilst lateritic weathering may extend to considerable depths, it is characteristically accompanied by a zonation in the weathering profile, evidence for which is not apparent in the kaolinised granites of Southwest England (Bristow, 1977; Bray and Spooner, 1983).

Fluid inclusion studies on both quartz from granites and hydrothermal vein minerals suggests that there were several different hydrothermal events in Southwest England. Several distinct high to moderate temperature fluids with moderate to high salinities have been identified in some of the hydrothermal vein systems, followed by a low temperature (70°C), possibly low salinity, fluid (Jackson and Wilson, 1977). It is generally believed that highly saline fluids will not result in the formation of kaolinite which is normally associated with fresh or acidic waters. The suggestion is, therefore, that kaolinisation is associated with low temperature, low salinity fluids indicating that it was a late, low-temperature event, quite separate from the saline fluids of the undoubted hydrothermal events.

Oxygen and hydrogen isotope ratios may be used to distinguish kaolinites of supergene and hydrothermal origin. Work on the isotopic composition of the kaolinite from the kaolin and ball clay deposits of Southwest England indicated that they are indistinguishable and the kaolin, like ball clay, resulted from weathering (Sheppard, 1977). Similarly scanning electron microscopy (SEM) has been used to point to a supergene origin for the kaolinite (Keller, 1976). SEM pictures of the kaolinised St Austell Granite show loosely packed, underformed, fragile stacks of kaolinite. The high porosity between the stacks implies that they formed under low hydrostatic pressure, that is near the surface. The texture of the SEM pictures of Cornish kaolinite are reported to closely resemble those of known supergene origin.

Some of this apparently contradictory evidence has now been reconciled by more recent studies. Fluid inclusion work has shown that not only does the quartz from within the kaolinised St Austell Granite contain more inclusions than unkaolinised areas, suggesting a higher level of hydrothermal activity in the former, but that these fluids also tend to be of low temperature and low salinity. The implication is that such fluids were responsible for kaolinisation and that their low temperature and salinity represents a late-stage influx of groundwater (Alderton and Rankin, 1983). A hydrothermal origin for the kaolinisation is also

favoured by Durrance *et al* (1982). Hydrothermal circulation associated with high temperature mineralisation (Sn, W) is thought to have both 'softened up' the granite, producing large areas of permeable matrix capable of allowing access to groundwater, and also caused deferruginisation of the mica thereby producing a low-iron parent rock. Radiogenically driven convective circulation of groundwater is considered to be the main, low temperature agency responsible for kaolinisation, a process believed to have been more or less continuous since Triassic times and which may still be continuing. The acidic nature of the low temperature fluid is thought to result from oxidation of near-surface sulphides. The meteoric origin of the kaolinising fluid, as suggested by stable isotope studies, is thus reconciled by these views. The most recent studies suggest a single stage, hydrothermal origin related to the formation of the quartz-tourmaline veins (Bray and Spooner, 1983).

St Austell Granite

The St Austell Granite has an area of about 93 km² and is extensively kaolinised in its central and western portions over an area of about 63 km². All the pits are concentrated in this area which is some of the most intensively exploited mineral-bearing land in the United Kingdom (Fig 7). The eastern part of the granite is relatively unaltered. The granite is by far the most important source of kaolin in the United Kingdom

Fig 7   Location of kaolin workings in the St Austell Granite.
(Based on Cornwall County Council, 1974).

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accounting for some 75 per cent of total production and a major proportion of the high brightness, speciality coating grades.

The granite has been mapped in terms of the presence or absence of K-feldspar megacrysts and biotite and the occurrence of lithium-mica and fluorite (Exley, 1959). The area of most intense kaolinisation and, therefore, kaolin exploitation was thought to coincide with the occurrence of lithium-mica in the so-called 'Early lithionite granite'. Moreover, the absence of an iron-bearing mica (biotite) in the host rock was also considered to be one of the main reasons for the very high brightness, and therefore high quality, of the kaolin from the St Austell Granite (Bristow, 1969). However, a more recent classification (Dangerfield and Hawkes, 1981) suggests that kaolinisation is not confined solely to the lithium-mica granite (Fig 8).

Fig 8   The distribution of rock types in the St Austell Granite.
(Based on Dangerfield, Hawkes and Hunt, 1980).

The St Austell Granite comprises three distinctive rock types (Dangerfield *et al*, 1980); a coarse-grained biotite granite containing feldspar megacrysts in varying proportions; a fine-grained granite, generally containing abundant megacrysts of feldspar, quartz and biotite and a non-megacrystic, medium-grained, lithium-mica granite. The latter locally shows alteration to 'gilbertite' (a greenish muscovite) and a fluorite-bearing material (the 'fluorite granite' of earlier classifications), possibly due to the affects of late-stage hydrous magmatic fluids. The coarse-grained megacrystic granite passes gradually in a westerly direction into a poorly megacrystic granite, the junction (Fig 8) being taken at an arbitrary 10 per cent megacryst content. The fine-grained granite appears to be included within the coarse-grained megacrystic granite as large irregular and sheet-like bodies, whilst the lithium-mica granite is thought

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to be intrusive into both coarse and fine-grained varieties. However, a metasomatic origin has not been dismissed (Dangerfield *et al*, 1980).

The pluton has been intruded by elvan dykes and quartz and quartz-tourmaline veins. Subsequent alteration has led to the partial, but preferred, destruction of plagioclase (mainly albite) over large areas resulting in the formation of the economically very important kaolin deposits. Kaolinisation has affected all granite types, the relative absence of iron-bearing minerals being an important factor in the formation of the high quality deposits. In the biotite-granite the biotite has often been altered to a colourless mica. The lithium-mica granite occurs principally in the west-central parts of the outcrop, including the small 'china stone' producing district to the north of St Stephen, although a much smaller body also crops out eastsoutheast of Hensbarrow Beacon, the highest point on the moor. China stone is a largely unkaolinised granite consisting principally of sodic plagioclase, K-feldspar, quartz and mica with small amounts of fluorite, topaz and apatite also present (Smale, 1979). The absence of iron-bearing minerals such as biotite and tourmaline make it suitable for use as a flux in the manufacture of bone china and modest quantities are produced for this and filler applications. China stone is the only indigenous source of feldspathic flux. Four grades are currently produced 'Hard Purple' (2 per cent CaF_2); 'Mild Purple' (1.5 per cent CaF_2); 'Hard White' (0.5-1 per cent CaF_2), and 'Soft White' (0.5 per cent CaF_2), the softer varieties having suffered a greater degree of kaolinisation. The change from kaolinised granite to hard china stone is gradational but takes place over only a few metres.

A study of the distribution of lithium in the St Austell Granite (Dangerfield *et al*, 1980) has shown that whilst the highest values coincide with the occurrence of the lithium-mica granite (mean 1615 ppm Li), there is also a zone of relative enrichment close to it in which biotite shows alteration to a pale-brown lithium variety. This zone is thought to represent an irregular metasomatic aureole around the intrusive lithium-mica granite and is equivalent to the 'Early lithionite granite' of Exley (1959). However, the low level of lithium in the western lobe of the St Austell Granite adjacent to the lithium-mica granite, together with the outcrop pattern and geomorphology, suggests a faulted junction. 'Gilbertisation' (muscovitisation) has significantly reduced lithium values, but kaolinisation has had little or no effect on lithium content.

The distribution of commercial grades is somewhat variable, most of the ceramic clays being produced in the western part of the granite around Treviscoe (Fig 7). Higher quality, paper coating grades are produced in the central and southern part of the granite. Further east the clays are of lower quality and suitable for general filler purposes (Menadue, 1979).

Dartmoor Granite

Current production of marketable kaolin from the Dartmoor Granite is some 500,000 tonnes a year (Vincent, 1982). Kaolinisation of economic

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importance has a restricted distribution on the Dartmoor Granite being confined to its southwestern edge in a belt stretching from Shaugh Moor through Lee Moor to Heddon and Hemerdon on the Crownhill Down Granite which is separated from the main granite mass to the north. The kaolinised granite consists predominantly of the coarse-grained, poorly megacrystic variety (Fig 4). The deposits at Hemerdon on the Crownhill Down Granite are not currently worked but are expected to be reopened during the mid-1990s.

Kaolin has been worked in the Lee Moor area since the 1830s. Elsewhere on the Dartmoor Granite there are sporadic indications of clay (Howe, 1914) in its southern part and there are disused workings at Red Lake, on Brent Moor near Knatta Barrow, at Leftlake and in the extreme south at Blackpool (Fig 9). Workings to the north of Shaugh Moor at Brisworthy on Wigford Down were abandoned in 1968.

Fig 9   Location of kaolin workings in the Dartmoor Granite

The workings on Lee Moor are on a very large scale and the existing Cholwich Town, Whitehill Yeo and Lee Moor pits will be amalgamated into one large pit which ultimately will be some 2,000 m in diameter. The clay in Wotter pit is contaminated by ironstaining and is not worked. High quality paper coating grades are produced from selected areas and are also present in the unworked Hemerdon deposit where clay to waste ratios are about 1:4.7, much lower than normal for the industry.

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The small Hemerdon Ball Granite is situated immediately to the south of the Crownhill Down Granite (Fig 9), with which it may be connected at depth. A sub-vertical, dyke-like granite body some 800 m long and 120 m to 150 m wide extends north-northeastwards from the main granite stock and carries significant tungsten and tin values in a sheeted quartz vein system. The Hemerdon deposit is the largest known tungsten deposit in Western Europe and contains mineable reserves of 38.2 million tonnes grading 0.183 per cent WO_3 and 0.029 per cent Sn. Development of the deposit is being proposed and, if plans come to fruition, the open pit mine will be one of the largest tungsten producers in the world with an annual output of about 2,200 tonnes of contained metal.

Intense kaolinisation, mainly restricted to the upper 30 m of the Hemerdon Ball Granite, gives way to fresh granite at depth. Consideration has therefore been given to its potential as a source of kaolin. However, the development of secondary iron oxides coincides with the areas of kaolinisation causing considerable staining of the clay. A small area of kaolinised granite at the southern end of the deposit contains commercial quality clay but the resources are small, about 650,000 tonnes with a yield of some 10 per cent. Separate extraction of kaolin has not been considered in the proposed mining operation.

Bodmin Moor Granite

The Bodmin Moor Granite consists chiefly of coarse-grained, megacrystic biotite granite, although locally it shows both an enrichment and deficiency in feldspar megacrysts. Finer-grained granite also occurs (Dangerfield and Hawkes, 1981).

Areas of kaolinisation occur mainly in the southwestern and northwestern parts of the granite and characteristically give rise to peaty depressions surrounded by high ground composed of unaltered granite. Topography is thus a good guide to the occurrence of kaolin deposits and weathering may have played a part in the formation of these deposits. Kaolin has been worked on Bodmin Moor since 1860 (Barton, 1966) and there are numerous abandoned workings. Only two pits, Park and Stannon Marsh, are, however, being worked and current production is some 150,000 tonnes a year. The clay is relatively low grade in terms of brightness and is used for general filler purposes.

Land's End Granite

The Land's End pluton consists of biotite granite of both coarse and fine-grained varieties, the former being the more widespread with the coarse-grained megacrystic variant the most common. As elsewhere, the major components of the biotite granite are quartz, K-feldspar, plagioclase and biotite. Kaolinisation has a limited distribution. The most important occurrence is a northwest-southeast trending belt some 1.5 km in length south of Lower Bostraze and 2 km east of St Just. One small pit at Bostraze is still in production with an output of about 5,000 tonnes a

year for use in the manufacture of insulation bricks. The working is in coarse-grained, poorly megacrystic granite and the kaolinisation, which is 50 to 100 m in width, is associated with a sub-vertical sheeted vein system consisting of greisen veins and quartz veins bordered with tourmaline. Disused pits lie along the same belt in the Balleswidden area to the southeast of Bostraze and further south on Bartinney Down. Old workings have also been recorded near St Buryan, 7 km east of Land's End and near Sancreed, 6 km west of Penzance (Barton, 1966). On the eastern margin of the granite, kaolin was formerly worked in fine-grained, biotite granite near Georgia, northwest of Ludgvan, and near Towednack, southwest of St Ives.

Tregonning—Godolphin Granite

The pluton consists of three major units (Stone, 1975); a fine-grained megacrystic biotite granite in the northern (Godolphin) part of the intrusion; a non-megacrystic, lithium-mica granite exposed in the southern part of the intrusion and around Tregonning Hill, and a Roof Complex consisting mainly of leucogranites and aplites with associated pegmatites, forming the roof of the Tregonning Granite. The lithium-mica granite consists of quartz, K-feldspar, plagioclase and a lithium-mica, with topaz and tourmaline as the main accessory minerals. The lithium-mica Tregonning Granite has undergone incipient kaolinisation in a number of areas but on Tregonning Hill the alteration is intense. Indeed china clay was first discovered and worked at this locality in 1746. The working lies at the northeastern end of a southwesterly trending belt some 1.5 km in length along which are a number of disused workings. Kaolin has not been produced from the Tregonning Granite since the First World War.

Elsewhere in Southwest England there was formerly a small production from the Carnmenellis granite at Porkellis Moor and also from the minor plutons of Belowda Beacon, Carn Marth and Hingston Down (Fig 5).

Other occurrences

Minor amounts of kaolin, perhaps amounting to a few hundred tonnes at most, were produced between 1887 and 1895 from the China Clay mine on the north side of Great Lingly Fell, Caldbeck Fells, in the northern part of the Lake District. The kaolin is associated with the northeast-southwest trending South Roughton Gill vein which was formerly worked at the Roughton Gill mines for lead, zinc and copper ores. Towards the northeast, metallic ores diminish and at the China Clay mine the vein, some 1 m to 2 m in width, consists of rotten sugary quartz containing umber which was also exploited. The vein dips towards the northwest, the hanging wall consisting of Borrowdale Volcanics. The Harestones Felsite, a pale greyish, semi-translucent rock with small phenocrysts of nearly white feldspar and automorphic quartz, forms the footwall. The Harestones Felsite is here highly altered and consists of a type of kaolin. A crosscut extends some 30 m into the footwall, all in kaolin with small

pockets of umber (Shaw, 1975). Samples of white 'clay' from the dumps contain only minor amounts of kaolinite along with mica and smectite, in the <15 μm fraction, the major constituents being quartz and feldspar. This material is probably not entirely representative of that worked but it appears to contain the necessary components for the production of white-firing ceramic bodies.

In the latter part of the 18th century an attempt was made to work 'china clay' in Derbyshire (Ford, 1964). The 'china clay' workings were apparently closely associated with the Pocket Silica Sand deposits to the west of Brassington, some of which contain nodules of white clay. The clay has been identified as halloysite and may represent the material used in pottery manufacture, although the quantities present are very small.

Kaolin occurs near Tresta on the Mainland of Shetland in a vertical zone of alteration in steeply dipping metasediments consisting of psammitic granulites and pelitic schist (May and Phemister, 1968). The vertical zone of kaolinisation ranges from 9 m to 30 m in thickness and is possibly up to 3.2 km in length, although the central part is obscured by peat and boulder clay. Well-ordered kaolinite is present but, whilst the clay content may be comparable to that of the Cornish deposits, it is of poor quality ranging from off white or pale yellow to reddish brown in colour. It was used locally in the 19th century as 'fuller's earth' and also for lining domestic hearths but it is unlikely to have any future economic significance.

Adjacent to the Perran Iron Lode near Perranporth in north Cornwall, the Lower Devonian country rocks ('killas') have been altered for up to about 30 m to a soft white kaolinitic clay by acid leaching from decomposing minerals of the lodes. The clay was formerly worked as a source of 'fuller's earth', although it does not contain montmorillonite (Sabine, 1968).

Sedimentary kaolin deposits of any significance are not recorded in the United Kingdom with the exception of certain ball clays in the Bovey Basin which appear to have been derived from the kaolin deposits on the Dartmoor Granite. However, the feldspar component of arkosic sandstones, for example in the Millstone Grit (Namurian) of the Pennines, has in places been altered to white kaolinite giving appreciable clay contents. Recovery of a kaolinite-rich fraction from the fines is thus feasible, for example, where the sandstones are worked for other purposes, but any iron oxyhydroxides present in the parent rock will tend to report with the clay product placing a major constraint on its economic value.

Properties and Uses

Kaolin is generally regarded as an essentially monomineralic clay composed of kaolinite and/or related clay minerals. Other minerals may, however, be present in significant quantities. English kaolins typically

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contain between about 75 and 85 per cent kaolinite in ceramic grades, and up to 94 per cent for finer-grained coating qualities. Of the other constituents, the most abundant is mica amounting typically to between 5 and 20 per cent of the marketable clay and accounting for most of the potash content of between 0.5 and 2.5 per cent K_2O (Noble *et al*, 1979). Small amounts of other minerals are invariably present, their quantity and nature determining the extent to which, for example, colouring impurities, abrasiveness and excessive viscosity in suspension may have a deleterious effect on the end product for particular applications. Speciality grades, such as paper-coating clays, contain only kaolinite and mica, but in others small amounts of smectite, quartz, tourmaline and feldspar may also occur, particularly in ceramic clays.

The industrial applications of kaolin are based on a combination of predominantly physical characteristics, different applications demanding distinct combinations of functional properties. Thus rarely are individual grades suitable for every application. Of fundamental importance to the commercial value of kaolin is the mineral's whiteness and its fine, but controllable, particle size, the latter of which also has a bearing on viscosity, colour and abrasiveness. Other important properties include its lamellar or platy particle shape, which increases opacity or hiding power, its soft (Mohs' hardness 2.5) and non-abrasive texture, due to the absence of coarser impurities, and its chemical inertness over a wide range of pH. In addition, some kaolins have important rheological properties, allowing them to be easily dispersed in water to produce slurries with low viscosities at high solids content, a factor of immense importance in the paper coating industry. Finally, an important attribute of kaolin is its relatively low price. Processing technology controls particle size allowing clays with specific size distributions to be produced. Similarly, advances in processing have made possible the removal of colouring impurities achieving substantial enhancement of whiteness. However, the production of low-viscosity clays from high-viscosity feed is not currently economically feasible.

An indication of the 'whiteness' of kaolin is obtained by measuring its surface reflectivity (brightness) at specific wavelengths of light compared with a perfectly reflecting standard. A perfectly white (and bright) material would produce total (ie 100 per cent) light reflectance within the visible spectrum. However, in commercial practice direct comparisons of 'whiteness' are usually made in blue light, normally at 457 nm (*see* Table 2) and the results are expressed as 'brightness' values.

Kaolin has a wide variety of industrial applications but by far the most important, accounting for some 80 per cent of total United Kingdom sales, is in papermaking. Other major outlets are in the ceramics industry (12 per cent) and as a filler/extender in paint, rubber and plastics (5 per cent).

Paper

Kaolin performs two quite separate functions in papermaking. As a *filler* or *loading* it is incorporated within the body of the paper, both reducing its overall cost and improving its printing properties. It is also a *coating* pigment, enhancing the surface properties of the paper, such as brightness, smoothness and gloss, and thus allowing the accurate reproduction of colour printing. Kaolin is therefore widely used in the coatings for the production of 'glossy' magazines. Of total United Kingdom sales of kaolin some 35 per cent is used in paper filling and 45 per cent for coating purposes, a reversal of the trend in the mid-1970s. Since kaolin improves the printing characteristics of paper, its major outlet is in the manufacture of printing and writing paper (*see* Table 1).

Table 1 Kaolin usage in paper

	Proportion of total European production %	Typical kaolin content %	Proportion of kaolin used	
			Coating %	Filling %
Type of paper				
Wrapping, packaging	30	0	0	0
Board	25	up to 10	10	5
Printing and writing paper	25	up to 30	90	85
Newsprint	15	up to 8	0	10
Tissue	5	0		0
Total	100	—	100	100

Source: D A Clark, 1977.

In Europe the three principal white mineral fillers used in papermaking are kaolin, calcium carbonate (chalk whiting and marble) and talc. Kaolin is by far the most important accounting for perhaps 70 per cent of the total market. The desired properties required of a paper filler are a fine, uniform and controllable particle size, softness and low abrasiveness (so that wear on papermaking machinery and printing type is reduced to a minimum), a high brightness, giving high light reflectance and increased opacity, chemical inertness, good retention characteristics between the cellulose fibres and a comparatively low price (Albert, 1958).

The principal component of paper is randomly orientated cellulose fibres; the air spaces or channels occupying the interstices between the fibres in fact constitute the bulk of the paper. Cellulose fibres are soft, white (when pure) and inert. Whilst the fibres are essentially transparent, light falling upon them is reflected in all directions making the paper appear opaque. Opacity or hiding power, which therefore represents the degree to which incident light is reflected or scattered from a surface, is an essential property in printing paper and is increased by the addition of white mineral fillers introduced to the stock at the start of the papermaking process. The opacifying properties of white mineral fillers depend on two factors—refractive index and particle size. The higher the refractive index of a mineral in relation to the medium in which it is

dispersed, the more effective it is at scattering or bending incident light. A large refractive index difference is therefore by far the most effective means of achieving good opacity. However, the refractive index of kaolin, at about 1.56, is very similar to that of cellulose fibre. The spacing of the individual particles from one another is also important and, since the mineral fills the voids between the fibres, it also increases the number of air-fibre and air-clay interfaces, increasing light scattering and thereby improving opacity. Opacity also improves with decreasing particle size, the best results being achieved at half the wavelength of visible light ie 0.3 μm. The incorporation of kaolin between the fibres also gives a smoother paper with good ink receptivity, improved printing characteristics and dimensional stability. Moreover, being significantly cheaper than cellulose fibre (wood pulp), it also helps to lower the overall cost of the paper. Whilst it may be desirable to increase the level of filler addition on the grounds of cost, high loadings have an adverse effect on paper strength by interfering with the fibre bonding, the strength-giving component of the paper. Typically printing and writing papers contain between 5 and 15 per cent kaolin fillers, although some papers may contain up to 30 per cent. Similarly, although finer particle sizes increase opacity and brightness, they are more costly to produce and their larger surface area also interferes with fibre bonding thereby reducing paper strength.

Titanium dioxide, with refractive indices in the range 2.55-2.70 and with particle sizes approaching the optimum, has a very high brightness and excellent opacifying properties. It is thus regarded as a white pigment. However, the very high cost of titanium dioxide compared with other white mineral fillers, and even woodpulp, limits its use to specialised applications where additional opacity is required. Calcined kaolin with a higher brightness, and thus opacifying properties greater than those of conventional filler clays, is produced from Georgia kaolin and is used to extend and, in some instances, replace costly titanium dioxide. However, calcined English clays tend to be somewhat more abrasive, due to a higher fluxing component, and are therefore not used in paper filling. The most important properties of filler clays are particle size distribution and brightness, typical values of which are given in Table 2. The coarser the clay the more abrasive it is likely to be because of the presence of more non-clay particles, ie feldspar, quartz.

For coating purposes kaolin is applied to the surface of the finished paper as a thin film of finely divided mineral suspended in water with an adhesive mixture such as latex, starch or casein. One of the main reasons for coating paper is to improve its surface properties so as to give enhanced images. Machine-made paper has an uneven surface which can be masked by coating to produce a smoother, brighter, glossier surface, ideal for high quality colour printing, the platy nature of kaolin allowing a very high degree of smoothness to be produced. The coating pigment must penetrate and bond satisfactorily to the sheet and, since kaolin is introduced to the surface of the paper as a suspension of high solids

Table 2. Typical compositions and properties of kaolins used in papermaking.

	Coating clays	Filler clays
	%	
SiO$_2$	47.8	48.7
Al$_2$O$_3$	37.0	36.0
Fe$_2$O$_3$	0.58	0.82
CaO	0.04	0.06
MgO	0.16	0.25
Na$_2$O	0.10	0.10
K$_2$O	1.10	2.12
TiO$_2$	0.03	0.05
Loss on ignition	13.10	11.19

Particle size distribution	%	
< 2μm	75-94	25-48
> 10μm	0.5 max	12-25
> 53μm	0.02 max	0.05 max
Brightness	85-88	76.5-84
Yellowness	4.2-4.7	—
Viscosity concentration	68-72	—
Mean typical surface area (m^{2}g^{-1})	10.5-12.5	6-8

Brightness is defined as the ratio, expressed as a percentage, of the radiation reflected by a body to that reflected by a perfectly reflecting white diffuser[1] measured at an effective wavelength of 457 nm with a Carl Zeiss Photoelectric Reflection Photometer.

Yellowness is expressed as the difference between the percentage reflectance values at 570 nm and 457 nm measured with a Carl Zeiss Photoelectric Reflection Photometer.

Viscosity concentration is defined as the percentage by weight of a chemically deflocculated pigment in an aqueous slurry which has a viscosity of 5 poise at 22°C when measured with a Brookfield RVF 100 Viscometer.

[1] An International Standards Organisation (ISO) BaSO$_4$ standard.

Data Source: English Clays Lovering Pochin & Co Ltd: Watts, Blake, Bearne & Co PLC; The Goonvean and Rostowrack China Clay Co Ltd and Steetley Minerals Ltd.

content, the clay suspension must have good flow characteristics to allow adequate spreading at high machine speeds. Particle size exerts the most influence on coating performance, contributing not only to the smoothness, gloss and printability of the coated sheet but also to the rheological properties of the coating slurry.

The combination of physical properties required for filler and coating grades of kaolin are significantly different. Coating demands special grades which are brighter and whiter with better glossing properties than filler grades. Since finer kaolinite particles have improved brightness, gloss characteristics and superior hiding power, coating grades are much finer than filler grades, having a much higher proportion of particles less than 2 μm equivalent spherical diameter (*see* Table 2 and Fig 10). Consequently they are less abrasive. Since they are applied to the surface of the paper at high speeds as a suspension of high solids content ($\sim$ 70 per cent), the rheology of the kaolin slurry is also of critical importance to give a smooth and complete coverage of the web. One of the main reasons, other than brightness, why many kaolins are unacceptable for

Fig 10 Particle size distribution of paper filler and coating clays

paper coating purposes, is their high viscosity in suspension, a property which cannot easily be improved by processing. High quality coating clays are comparatively rare commodities and are consequently more expensive than filler grades.

The physical criteria of most importance to the paper industry are, therefore, particle size distribution, brightness, viscosity and abrasiveness.

Ceramics

Kaolin was originally used in the manufacture of whiteware ceramics. The amount of kaolin used for this purpose is now greatly exceeded by that used in the paper industry but the ceramic and refractories industries still remain a major market, accounting for nearly 1 million tonnes of kaolin in Western Europe. The major markets for English kaolins in the whiteware ceramics industry are vitreous-china sanitaryware, tableware, wall tiles (in the UK), electrical porcelain and glazes. In addition, kaolin and calcined clay are also used for refractory applications. Typical body compositions for the principal varieties of whiteware, including the main tableware bodies—earthenware, bone china and porcelain, are shown in Table 3.

In a ceramic body the clay component contributes to plasticity, workability and strength in the pre-fired state, and to strength in the fired body, since it contributes to mullite formation, thereby reinforcing

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Table 3. Typical body compositions for whiteware ceramics

	Wt % total solids				
	Kaolin	*Ball Clay*	*Flux[1]*	*Quartz[2]*	*Others*
Earthenware	25	25	15	35	—
Porcelain	60	10	15	15	—
Bone china	25	—	25	—	50 Bone ash
Vitreous-china sanitaryware	20-30	20-30	15-25	30-40	0-3 Talc
Electrical porcelain	20	30	30	20	—
Wall tiles	20	30	—	30-35	10-12 Lst.

[1] Usually K-feldspar, nepheline-syenite or china stone.
[2] Silica sand and calcined sand or flint.

the finished product. However, kaolin has a low plasticity and low dry strength, due mainly to its coarse particle size, and it is not used as a plasticiser in most ceramic bodies, a function performed by kaolinitic ball clays. However, in bone china and porcelain bodies kaolin is the only clay constituent. Kaolin's main function is to confer whiteness to the ceramic body and, unlike its use in the paper industry, it is the fired (as opposed to the natural) brightness of the clay which is important. Typical fired brightness values at 1180°C (earthenware temperatures) are 83-91 per cent. A low iron content (<0.9 per cent Fe_2O_3) is therefore essential, as is the absence of discrete iron-bearing minerals such as biotite and tourmaline which may produce discoloured specking on the surface of the fired product.

Some kaolins contain small amounts of smectite resulting in appreciable increases in the plastic properties, modulus of rupture (strength) and shrinkage of the clay. Smectite also increases the viscosity of clay/water suspensions, of considerable importance in slip casting where the slip is required to be very fluid but, at the same time, contain a high proportion of solids, since excess water has to be absorbed by the mould. In small amounts the presence of smectite can be beneficial since it will increase the green and dry strength of the clay. However, because of its very much finer particle size, increasing amounts of smectite reduces casting concentration (the maximum amount of clay that can be added to give a standard slip) and casting rate (the rate of clay build-up in the plaster mould), and increases deflocculant demand (the amount of deflocculating agent required to produce a standard viscosity at the casting concentration).

Ceramic clays are assessed against a range of physico-chemical and ceramic properties. However, consistency in quality is of paramount importance to ceramic manufacturers rather than the absolute values themselves. Primary control properties include particle size distribution, which has a bearing on the strength and casting properties of the clay, potash content, relating to mica and feldspar content and affecting firing shrinkage, total iron, influencing fired colour, and alumina which gives an indication of the kaolinite content or purity of the clay. The range of

ceramic properties assessed include modulus of rupture (strength), casting concentration, deflocculent demand and casting rate; and fired brightness, linear shrinkage and water absorption at the various firing temperatures for standard bodies. A number of these properties are shown in Table 4. In products such as bone china and some porcelain bodies which do not incorporate ball clays, the dry strength of the clay is important. Since strength is usually a function of particle size, finer-grained clays are produced for this purpose. These clays should also have a high brightness. Conversely in sanitaryware, which is slip cast into a plaster mould, a considerable thickness of clay has to be built up rapidly on the walls of the mould. This is best achieved by relatively coarse-grained clays, which will tend to have a low modulus of rupture. Clays for earthenware bodies are intermediate between the two.

Table 4.   Compositions and properties of kaolins used in ceramics

| | Wt % | | | | |
	1	2	3	4	5
SiO_2	48	48	48	48	48.8
Al_2O_3	37	37	37	36.3	36.1
Fe_2O_3	0.65	0.70	0.85	1.0	0.62
CaO	0.07	0.06	0.07	0.1	0.12
MgO	0.3	0.3	0.3	0.3	0.35
Na_2O	0.1	0.1	0.1	0.1	0.14
K_2O	1.6	1.85	1.75	1.8	2.60
TiO_2	0.02	0.02	0.05	0.1	0.07
Loss on ignition	12.5	12.5	12.1	12.3	11.20
$\% < 2\mu m$	70	57	40	50	48
$\% > 10\mu m$	4	10	18	4	14
$\% > 53\mu m$	0.03	0.05	0.10	0.06	0.15
Modulus of rupture at 110°C (Kgf/cm²)	31.7	25.7	10.9	7-11	25
Brightness at 1,180°C	91(a)	86(a)	86(a)	85(b)	83(c)
Brightness at 1,280°C	88(a)	86(a)	87(a)	—	—
Brightness at 1,410°C	77(a)	75(a)	—	—	—

(a) at an effective wavelength of 457 nm;
(b) at 464 nm;   (c) at 495 nm.

Source:
1. 'Standard Porcelain'   ECLP. High quality tableware, porcelain and bone china.
2. 'Grolleg'   ECLP. Earthenware tableware.
3. 'Remblend'   ECLP. Sanitaryware.
4. 'CC 31'   Watts Blake Bearne & Co PLC. Sanitaryware and general purpose ceramic clay.
5. 'Diamond Ceramic'   The Goonvean Rostowrack China Clay Co Ltd. Ceramic clay including bone china.

Kaolin has limited uses in the refractories industry, its main application being in the production of insulation bricks. However, specially selected clays (Al_2O_3 >36.5 per cent; K_2O <1.75 per cent and Fe_2O_3 <0.9 per cent) are used in the production of a refractory chamotte used principally in pottery kiln furniture (50 per cent) and for investment castings (20 per cent).

Paint

Both natural and calcined kaolin are used as extenders in a range of paint formulations, although interior emulsion paint is by far the most important sector. In addition to reducing the overall cost of the paint, kaolin also imparts certain beneficial properties, although it is usually used in combination with other extenders. Opacity or hiding power, an important property in paint, as it is in paper, is a function of refractive index and particle size—fine particles giving increased opacity and whiteness. The lamellar shape of kaolinite also improves opacity compared with more equi-dimensional shaped particles such as calcium carbonate. The opacity of paint improves with increasing levels of extender (Huxtable, 1980). Whilst kaolin cannot be considered as a white pigment, it does serve to 'space out' the expensive white titanium dioxide particles, giving maximum light scattering and thus optimising its opacifying properties. The fine particle size, good dispersibility, lamellar structure and presence of active sites on the faces (negatively) and edges (positively) of the kaolinite particles also impart important rheological properties to the paint. As a result the dispersed kaolinite particles build up a thixotropic structure which prevents pigment settling in the can but which breaks down on application to give good brushing characteristics. In general, the finer the particle size the greater the thixotropy. The lamellar particles also overlap on application to reinforce the final paint film.

Calcined clays are being increasingly used in paint formulations because of their particle shape and high brightness (up to 90 per cent) and thus improved opacity compared with natural clays. Calcination also produces harder particles which impart greater durability to the paint.

Rubber

Kaolin is incorporated into both natural and synthetic rubber compounds and is the rubber industry's most widely used non-black filler with reinforcing properties. Two basic varieties of kaolin are used, semi-reinforcing or 'hard' clays, and essentially non-reinforcing or 'soft' clays. The major distinction between the two varieties is particle size and hence surface area, 'hard' clays being much finer with 75 to 80 per cent $<2\mu m$, compared with 20 to 45 per cent $<2\mu m$ in the case of 'soft" clays. The choice of filler is determined by the required properties, performance and application of the rubber compound. 'Hard' clays enhance the physical properties of the rubber compound by, for example, increasing modulus of rupture, tensile strength and imparting good resistance to wear and abrasion, of particular importance in moulded footwear. In this respect they are, however, not as effective as carbon black which reacts with the rubber and so their use is confined to coloured compounds used in conjunction with a pigment. In contrast, 'soft' clays are used principally as an inert filler to lower the overall cost of the product without excessively impairing its mechanical properties. The hexagonal, plate-like particle shape of kaolinite increases the viscosity and stiffness and thus green strength of the compound, leading to dimensional stability and

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smooth surfaces in extrusions (Pickering, 1978). Silane treated clays also give enhanced reinforcing properties in rubber and these are now being placed on the market.

Rubber containing calcined clays has different properties, including improved colour, improved electrical insulation properties, low free moisture, low water absorption and improved durability. The most common application of calcined clays is in cable insulation compounds but other uses include the production of intricate mouldings and extrusions because of the smooth, glossy surfaces that can be produced. The clay content of coloured pharmaceutical rubber mouldings, such as stoppers, now consists almost entirely of calcined clay.

Plastics

Kaolin has only a limited use as a filler in plastics, for example, in PVC flooring compounds. However, low temperature calcined clay has important applications in the cable industry as a filler in PVC for sheathing and insulation purposes. Because of its high volume resistivity, calcined clay is particularly suitable for high voltage insulating compounds where high electrical resistance is required.

White cement

In the production of Portland cement commonly occurring clays usually provide the necessary silica, alumina and iron oxides which, together with a calcareous raw material, form the calcium silicates and aluminates present in cement clinker. In the production of white cement, iron is a deleterious component which can be avoided by using kaolin, an alumino-silicate with a very low iron content. Silica sand is required to make up the resultant silica deficiency in the raw feed.

Glass fibre

The preferred raw material for introducing alumina to glass compositions for glass fibre manufacture is kaolin. Alumina improves the durability and mechanical strength of glass and, in most types of glass, it is introduced in the form of feldspar or nepheline-syenite, the high alkali content of these two minerals being an added advantage since it acts as a flux. However, for continuous glass fibre for reinforcement purposes, the most common glass composition is so-called 'E' glass, a calcium-magnesium-aluminium-borosilicate glass characterised by an alkali content of less than 1 per cent when calculated as Na_2O. Kaolin is used therefore as a low alkali source of alumina. Coarse quartz particles are a serious impurity in glass fibre manufacture and must be less than 20 particles/kg of clay.

Agricultural industries

The caking or setting of granular fertilisers (prills), particularly those with a high nitrogen content, is a serious problem since the caked mass must be broken down to its individual particles before it can once again

become a free-flowing product. A variety of anti-caking agents is used but, since fine particle sizes have been found to be most effective, clays are widely favoured, their plate-like shape and thus high surface area being an additional advantage. Kaolin, some of which is amine-coated, acts as a non-stick coating to the fertiliser prill. As colour is of no significance, cheaper grades of kaolin can be employed.

Kaolin acts as an inert carrier for insecticides, pesticides and weedkillers, the clay providing the means of transporting the active ingredient and allowing its release at a controlled rate.

Other industries

Kaolin has a wide range of other applications. The highest purities are used in small amounts for pharmaceutical applications in 'Light Kaolin' and 'Heavy Kaolin', both materials having to comply with British Pharmacopoeia specifications regarding purity and inertness. Light kaolin is of a finer particle size and is used internally as a carrier for active ingredients in, for example, stomach medicines and tablets. Heavy kaolin is used externally.

In certain types of high quality leather kaolin is used in dressings to fill the pores and produce a smoother surface and in textiles kaolin is used for sizing and strengthening the fibres of cotton yarn prior to weaving. Kaolin is also used in inks, dyes, adhesives, crayons and pencils, in certain tooth-pastes and some cosmetic applications where it may be used as a diluent for talc. In the chemicals industry the mineral is also being used as a binder in the production of zeolite catalysts extensively used in cracking petroleum.

Alternatives to kaolin

Most mineral fillers are valued because of their colour (brightness), fine particle size and relatively low cost. A number of white minerals may therefore be used as alternatives to kaolin for filler applications, the most important in Western Europe being calcium carbonate and talc. Availability and cost are important factors in their use but, whilst current consumption in comparison to kaolin is still relatively small, increasing interest has been shown, particularly in calcium carbonates, for both paper filling and coating applications.

Until the early 1950s calcium carbonate could not be used as a paper filler because of the acid environment produced by the rosin/alum sizing systems used (the function of which is to make the paper more water resistant). Calcium carbonate fillers can be protected from these acid conditions by coating with starch and a polymer, but the resultant product is expensive. More recently, however, the introduction of synthetic sizing systems has enabled sizing to be carried out under neutral or alkaline conditions thereby allowing the use of unprotected calcium carbonate fillers. Paper made under alkaline stock-preparation systems

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has a greater strength and dimensional stability and is more durable than paper produced by conventional acid systems, allowing loading with increased quantities of filler (up to 30 per cent). This factor, coupled with other improvements in paper technology, has resulted in an increased demand for high quality, low cost calcium carbonate fillers for both writing and printing papers in Europe and North America. In Europe, the main source of calcium carbonate is natural chalk whiting derived from the Cretaceous Chalk, although high purity chalk with a sufficiently high brightness has a relatively restricted distribution. However, marble, such as the Carrara deposits at Massa in Italy, may have an exceptionally high brightness.

As with kaolin, chalk fillers show similar improvements in optical properties (opacity and brightness) with decreasing particle size. Standard chalk fillers have particle sizes in the range 30 to 50 per cent $<2\ \mu m$ and have ISO brightness values of 81 to 82 per cent. For finer particle sizes in the range 80 to 90 per cent $<2\ \mu m$, brightness values increase to about 86.5 per cent. However, the adverse effect on paper strength with finer particle sizes is markedly less for chalk than clay, possibly because of the fundamental difference in their particle shapes and the much smaller surface area of chalk at comparable size distributions resulting in less interference with the fibre bonding (Brown, 1981). Comparison of the properties of some clay and chalk fillers is shown in Table 5.

Table 5 Physical properties of some clay and chalk fillers

	Brightness %	Yellowness %	>10 μm %	<2 μm %	Mean surface area m²g⁻¹
Grade B clay	82.5	5.2	12	45	8
Grade C clay	81	5.2	12	45	8
Chalk	82	5.9	18	9	2.6
Chalk	81	5.9	9	43	2.6

The ability to use higher loadings of fine, low cost chalk fillers which permit good opacity and brightness to be achieved without loss of paper strength will be a factor of increasing importance in view of the continuing need to reduce papermaking costs. Nevertheless, capital investment in acid sizing systems is considerable and change will not come quickly.

In paper coating a distinct disadvantage of natural chalk whitings is their relatively coarse size with a significant proportion of the material $>10\ \mu m$. This adversely affects the gloss characteristics of the paper and therefore its printing quality. High purity precipitated calcium carbonates are available but often at a higher cost than coating grades of kaolin. More recently, very fine coating grades of carbonate (>80 per cent $<2\ \mu m$) have been introduced. Those based on natural chalk whiting have brightness values (86.5 per cent) comparable with coating grades of kaolin whilst carbonates based on the Carrara marble deposits, which are

the most widely used, have significantly higher brightness values (90-93 per cent). Their low cost, high brightness and low adhesive demand are important properties but carbonates also improve the viscosity characteristics of the coating colour allowing formulations of high solids content to be applied at higher coating weights, with consequent energy savings (Anon, 1982a).

Table 6   Physical properties of clay and calcium carbonate coating pigments

	Brightness	Yellowness	>10 μm	<2 μm	Mean surface area
	%	%	%	%	m^2g^{-1}
Coating clays	85.5-87.5	4.2-4.7	0.2-0.5	75-95	10.5-12.5
Carrara marble	93	1.5	0.1-1.5	75-90	9.0-13
Chalk	85.5	4.1	1.0-1.5	80-90	6.0-8.1

Coating pigments can be produced with combinations of clay and carbonate content to give the desired gloss or matt finish.

Calcium carbonates are showing the fastest growth of all the main raw materials used by the paper industry. In 1979, carbonates accounted for 13 per cent of total Western European coating pigment and this proportion is forecast to increase to 18 per cent by 1984, with an installed capacity of coating carbonate of 580,000 tonnes (Anon, 1980).

Technology

Unlike many sedimentary kaolin deposits, no natural concentration of kaolin has taken place in the primary deposits of Southwest England and thus the kaolinite content of the clay matrix is relatively low. However, kaolinite occurs mainly within the size fraction finer than 20 μm and processing therefore consists of rejecting the coarser impurities, principally quartz and micaceous minerals, by classification in water. Other processes are used for modifying the properties of the kaolin product by enhancing brightness and producing specific size fractions. Normally, no size reduction occurs during wet processing, the kaolinite being merely dispersed into its natural particles. Wet processing results not only in a product of very high grade in terms of kaolinite content (>75 per cent), but also a clay product of exceptionally high quality in terms of brightness and one with a controllable particle size distribution. Subsequently, the kaolin is further treated for sale in slurried, dried or calcined form.

The sedimentary kaolin deposits of Georgia, in contrast to the English deposits, have a much higher kaolinite content, containing over 80 per cent clay as dug, and a more uniformly fine particle size, from 60-70 per cent <2 μm for Cretaceous kaolins to >90 per cent <2 μm for Tertiary kaolins. The clay may be processed for sale by dry, air-float methods or, for more refined products, by wet classification. English kaolins have a natural whiteness superior to that of the Georgia clays. However, with a

coarser natural particle size, the emphasis in refining English kaolins is placed on producing grades with consistent and specific fine particle sizes.

Mining

In Cornwall and Devon kaolin is extracted by hydraulic mining following the removal of overburden, consisting of weathered and discoloured granite as well as peat, soil and other superficial deposits. Overburden may be up to 15 m thick, although it is usually considerably less, except where waste tips from former workings have to be removed. Current practice for the most part allows tipping only on unkaolinised granite to prevent sterilisation. Remotely controlled automatic monitors producing high pressure jets of water at up to 2.45 MN m^{-2} are used to disintegrate the friable, kaolinised granite and to disperse the kaolinite into suspension. Pit faces, which are known locally as 'stopes', are worked where possible in 18 m benches to maintain slope stability. Variation in clay quality, due mainly to the presence of accessory minerals and iron oxides, may be considerable, both within the confines of a single pit and from area to area. Although present in very small quantities, accessory minerals such as smectite and iron-bearing minerals are very significant in determining the quality and ultimate end use of the clay. However, evaluation of borehole samples allows specific grades to be blocked out in advance of mining and frequent stope sampling during working provides a fairly accurate delimitation of particular grades so as to facilitate selective extraction. In the larger pits it is usual to have ten or twelve monitor positions of which about three are worked simultaneously. This allows blending of the resultant slurries to even out any variations in clay quality. In this way lower grade clays can be utilised by blending. Since different qualities of clay may be present in the same pit, the working of selected stopes allows a range of grades to be produced. Subsequent blending of slurries from several pits in central refining plants is now normal commercial practice so as to improve quality control and to produce standardised grades and ensure optimum use of the resource.

The physical characteristics of the clay matrix may vary significantly in relation to the geometry of the whole deposit. The clay matrix becomes softer and more productive as quartz/tourmaline veins are approached and clay yields tend to increase towards the centre of the deposit. In general, the clay matrix becomes more productive and of higher quality with depth. There are, however, limitations to working to greater depths since the deposits become narrower and in order to maintain slope stability, increasing waste to clay matrix ratios are encountered. Currently pits are worked to a maximum depth of about 100 m.

Kaolinised granite may grade rapidly over less than a metre into unkaolinised granite which, together with quartz/tourmaline material, is waste and known locally as 'stent'. This material may have to be blasted and subsequently removed from the pit by truck and shovel. Similarly, kaolinised granite badly stained by iron oxides must also be removed as

waste. Ripper/dozers are used to break up partially kaolinised rock and to transfer it to the monitors for disaggregation, a technique which is being more widely used to increase yields and to allow further selectivity in mining.

The slurry produced by hydraulic mining, which contains kaolinite particles, gravitates to the base of the pit (the sump). Sufficient gradient is maintained on the pit floor to allow all the disaggregated debris, including coarse sand, to be washed into the sump. Here centrifugal gravel pumps mounted on inclined carriageways, allowing them to be raised or lowered, lift the slurry to spiral sand classifiers. Clay fines with low settling velocities are carried away in the liquid overflow, whilst other material (mainly coarse quartz and some unaltered granite) is discharged as waste. This quartz sand waste is removed by inclined conveyors to tips; only a minor proportion is sold for aggregate purposes. The traditional, pyramidal shaped tips, which formed a characteristic feature of the Cornish landscape, have now been replaced by a flattened, terrace form to achieve greater stability. The overflow ($<250 \mu m$) from the spiral sand classifiers, containing kaolinite, fine quartz and mica, is then pumped to banks of primary hydrocyclones where the second stage of particle size classification begins. The largest pits have capacities of about 10,000 tonnes a week in terms of clay produced with as little as 1,000 tonnes a week in the smaller workings.

Because of the relatively low kaolinite content (10-15 per cent) of the deposits, large volumes of waste are generated and disposal remains a constant problem to the industry. Some 40 to 60 per cent of the original rock is discarded as sand. Typical clay to coarse sand and clay to micaceous residue ratios are approximately 1:3.5 to 5 and 1:0.5 to 1 respectively. In addition, large quantities of 'stent' and overburden may also be produced. Only small quantities of sand are sold locally for construction purposes in ready-mix concrete and block-making. Typically, 8.5 tonnes of waste, comprising 6.5 tonnes of sand and stent, 1 tonne of overburden and 1 tonne of micaceous residue are generated in the production of 1 tonne of marketable clay.

The ratio of waste to clay production may, however, vary appreciably depending on the nature of the deposit and amount of stent and overburden. Improved recovery methods have also reduced the loss of coarser kaolinite particles into the micaceous residue, thereby increasing overall yields and, in some places, it will now be possible to re-treat micaceous tailings for their kaolin content which may be as high as in the original clay matrix.

Refining

The two principal objectives of clay refining are the removal of impurities and the production of a desired particle size distribution. Little or no size reduction of the kaolinite particles takes place. Wet classification of fine particles is governed by Stokes' Law, which states

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that the settling velocity of a particle (V_{max}), after its initial acceleration, is given by the equation:—

$$V_{(max)} = \frac{d^2 g(D_s - D_f)}{18\eta}$$

where V = maximum velocity of the particle m s^{-1}
   d = particle (sphere) diameter (m)
   g = acceleration due to gravity (m s^{-2})
   D_s = particle density (kg m^{-3})
   D_f = fluid density (kg m^{-3})
   η = fluid viscosity (Ns m^{-2})

Thus, in free settling conditions, the velocity depends on the square of the particle size and is otherwise directly proportional to effective density, fluid viscosity and gravity. Hence the principle offers a very sensitive basis for separating particles by size, provided that no great differences in density are involved. Particle shape is also an important factor, although not represented in the equation in which 'd' refers to the diameter of a sphere (hence particle size is described in terms of 'equivalent spherical diameters'). The shape factor is difficult to quantify but it is mainly related to the cross sectional area of the particle that contributes a resistance to the motion. Hence a plate-like shape tends to inhibit motion compared with a sphere.

Clay refining involves separating fine platy kaolin particles from coarser quartz, feldspar and mica. There is little density difference between any of the minerals. The quartz and feldspar being relatively coarse and spherical are easily removed, as is the coarser mica. Only the finer particles of platy mica are difficult to separate from the kaolin and mica is therefore the major impurity in the marketable product.

Particle settling velocities may be increased by centrifugal forces. Hydrocyclones, which are more suitable for particles coarser than 5 μm to 10 μm, and centrifuges, which can make separations at less than 2 μm, are widely used in the industry. In hydrocyclones the finer, slower moving particles migrate to the low pressure axial zone and are discharged as overflow.

The overflow from the spiral sand classifiers is pumped to primary hydrocyclones, where fine quartz and coarse mica greater than 53 μm is removed in the underflow which is pumped to the mica dams as waste. Subsequent refining differs somewhat throughout the industry. The smaller producers, because of their lower throughputs and the lower capital cost of the equipment, use secondary and tertiary hydrocyclones of successively smaller diameters to recover the finer size fractions. However, the process adopted by English China Clays is described here (Menadue, 1979) since it accounts for the bulk of UK production.

The overflow (<53 μm) from the primary hydrocyclones, consisting predominantly of kaolinite but also still containing appreciable amounts

overburden removal

quarry face

QUARRY EXTRACTION

mainly quartz sand
with coarse mica and
unkaolinised feldspar
to waste tips

pressure water hose
(monitor)

gravel pump

>250 μm

hosepool water pump

spiral classifer

<250 μm

raw clay
95% < 53 μm

slurry pump

process residues to
mica storage
lagoon

hydrocyclones

sump

hydrocyclone pump

fine sand and mica
>53 μm

DEWATERING TANKS
(raw clay thickening to 30% solids)

98% >2 μm

water

clay

DORR OLIVER
REFINING
TANKS

clay suspension
marketable clay
99·98% < 53 μm
85 % < 10 μm
45 % < 2 μm

REFINED CLAY
STORAGE UNITS

water

>15 μm

centrifuge coarse residue

ultraflotation

sand grinding

filler clay

coating clay
99·5% <10 μm
75% <2 μm

waste

filler clay

water screens

DRYING UNITS

water

filter presses
(plate and tube)

tube pressed
clay

storage linhays

fluid bed
rotary
buell
drum
spray

bulk shipment   bagged shipment   powdered shipment via   calcination
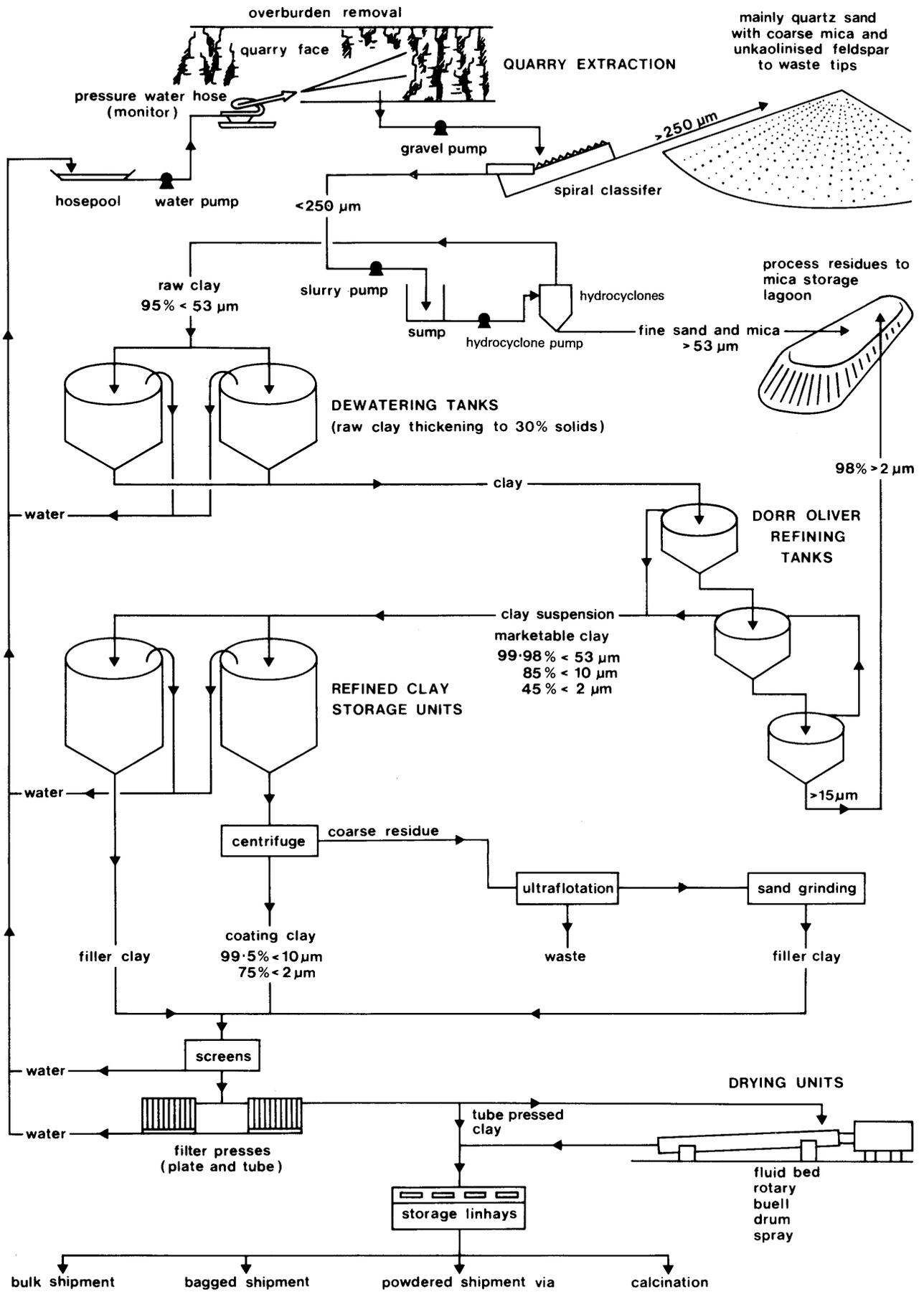   disintegrating mill

Fig 11 Flow diagram of kaolin production and refining

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of impurities, is pumped to circular raked dewatering tanks where the flocculated clay particles settle to produce a thickened slurry containing some 30 per cent solids. Supernatant water is recycled to the monitors.

There may be an appreciable variation in the properties of the clays from different stopes and pits and slurry samples are, therefore, routinely checked against a range of criteria. The results are fed to a computer which selects appropriate amounts of the various slurries for blending to produce standardised grades. Consistency is of critical importance to the consumer. At the central refining plants the thickened clay is dispersed and passed to a series of up to four raked circular refining tanks (hydroseparators) from 14 m to 20 m in diameter. An upward moving current through the deflocculated slurry causes a separation of the fine fraction containing kaolinite which overflows the rim of the tank. The particle size of the overflow is determined by controlling the rate of flow to the tanks. The coarse fraction (>15 μm), consisting mainly of mica and coarse-grained kaolinite along with some fine quartz and unkaolinised feldspar, is raked to the centre of the tank and discharged into the next tank in the series for further refining to remove any residual clay. The remaining coarse residue, which should be 98 per cent >2 μm, is rejected. The overflow from the first two refining tanks, which should be at least 99.98 per cent <53 μm, 85 per cent <10 μm and 45 per cent <2 μm, provides a marketable product as a general purpose filler. The overflow from the succeeding tanks is recirculated. For the production of speciality grades, such as paper coating qualities, the blended filler product may, if of adequate quality, be further treated in solid bowl centrifuges which allow separation at very much finer particle sizes than hydrocyclones. A very fine-grained product, consisting of at least 75 per cent <2 μm, 99.5 per cent <10 μm, and 99.99 per cent <53 μm, is produced in this way for paper coating purposes. Secondary centrifuges scavenge the coarse residue from the primary centrifuges and the fine product may be recirculated, if of adequate quality, or more usually blended with the refining tank overflow for filler use. The flow sheet is shown diagrammatically in
Fig 11.

To improve the recovery of speciality clays new processes have been introduced. Since larger mineral particles settle out faster, there is some loss of coarser kaolinite into the coarse residue in the secondary centrifuges, which contains about 4 per cent <2 μm. This loss has been overcome by the development, by English China Clays, of an ultra-fine flotation method. The kaolinite particles are rendered hydrophobic (water repellent) by the addition to the pulp of a chemical reagent (collector). The particles preferentially attach themselves to air bubbles rising through the flotation cell and are removed in a froth from the top of the cell. The underflow is rejected. Good separation between the coarser kaolinite particles and other coarse-grained impurities is essential to produce a low abrasion product. The flotation product is then fed to low-solids sand grinding units, where attrition breaks up aggregates of kaolinite particles and reduces the <10 μm fraction to maximise clay recovery in the <2 μm

fraction. The degree of comminution is controlled by throughput and, with a closed circuit, a very fine-grained product can be produced. The sand grinding medium is removed by hydrocyclones.

Other beneficiation processes

The principal colouring components in kaolins are iron-bearing impurities and fine-grained anatase (TiO_2). These tend to be more abundant in sedimentary rather than in primary kaolins. For example, Georgia kaolins have a high TiO_2 content with the Tertiary clays containing between 2 and 8 per cent submicron anatase. The removal of colouring oxides is essential if high brightness or, in some cases, even marketable grades are to be produced. One method adopted in the United Kingdom, Georgia and elsewhere in recent years is the use of high gradient-high intensity wet magnetic separators which allow the selective capture of weakly paramagnetic micron-sized particles from a clay slurry. These impurities are captured on ferromagnetic stainless steel wire wool enclosed in a canister which itself is within a strong magnetic field. Kaolin slurry is fed upwards through the canister and the magnetic field energised. The flow rate is controlled to give the desired retention time and the flow is distributed evenly across the area of the steel wool matrix.

The canister is cyclically de-energised and flushed out with water to remove magnetic particles coating the steel wool and periodically needs manual cleaning. Although English kaolins have a high natural brightness, magnetic separation has been used since 1976 to remove iron-bearing minerals, in particular, mica (biotite and zinnwaldite) and some tourmaline, and also iron oxides staining the clay, so as to upgrade raw material for the production of ceramic grades where fired colour and the absence of specking is of critical importance. However, because of the cost, only a small proportion of total output is treated in this way. Magnetic separation achieves at least a 40 per cent reduction in Fe_2O_3 content and a 5 to 6 unit gain in fired brightness at 1180°C (Lofthouse and Scobie, 1979). The process allows a wide range of feed material to be mined including yellowish to orange stained clays which, with Fe_2O_3 contents in excess of 0.7 per cent (the specification for most ceramic grade clays), would otherwise have to be rejected as waste. Typically, the iron content can be reduced from 0.8 to 0.6 per cent Fe_2O_3 with a 90 per cent recovery (Noble *et al,* 1979). During magnetic separation the potash content falls in line with iron, indicating that iron is mainly associated with the micaceous mineral.

Chemical bleaching is a standard technique to improve the brightness of both filler and coating grades, although the process is not used as widely in the United Kingdom as elsewhere because of the inherently higher brightness of English clays. The addition of a strong reducing agent, usually sodium dithionite ($Na_2S_2O_4$), in an acid environment, reduces ferric (Fe^{3+}) to ferrous (Fe^{2+}) iron which whitens the clay, resulting in a 2 to 4 point increase in brightness. Ferrous iron with a higher solubility than ferric iron, allows a very small proportion of the total iron to be

removed in solution. However, iron-bearing minerals and iron contained in the kaolinite lattice are untouched. Ozone and chlorine may also be used to oxidise organic matter and thus enhance brightness.

Elsewhere, the kaolin industry has introduced other techniques to improve the brightness of paper coating grades and these have been reviewed by Coope (1979). In addition to magnetic separation, froth flotation is used to remove iron and titanium-bearing minerals from kaolin but these methods become less efficient in size fractions less than 80 per cent <2 μm. A two-liquid separation technique similar to froth flotation, except that an organic liquid (kerosene) replaces air bubbles, has been found to be effective in removing anatase from American kaolin and tourmaline from English clays at fine particle sizes (Shergold and Lofthouse, 1980) but this is not yet in commercial operation.

Dewatering and drying

Dewatering and drying are necessary to bring the clay product to shipping grade form. Dewatering by thermal drying is energy intensive and therefore costly (Hoskins and Webster, 1983). Consequently mechanical dewatering by high pressure filtration is now achieving greater importance.

Prior to dewatering the kaolin slurry is screened to remove any contaminating material. Centrifuges are used to produce an initial thickened product for the finer-grained paper coating grades. The standard dewatering method in the United Kingdom has been to utilise conventional plate filter presses which produce a cake of about 30-35 per cent moisture content. These have, in part, been replaced by high pressure (70 bars) plate presses developed by English China Clays which can produce filter cake at 25 per cent moisture in about half the time of the standard presses. Unlike filter cake from low pressure presses, the product can be dried directly without the need for mixing with pre-dried material. High pressure filter presses are used for fine particle size coating clays. Vertical tube presses (working at 100 bars) have also been developed by English China Clays which can reduce the moisture content of filler clays from 78 per cent to 17 to 18 per cent. The filter cake is hard and free-flowing and can be marketed without the need for any subsequent drying. However, this process is not suitable for dewatering fine coating grades. Particle size distribution and smectite content may appreciably affect the time taken for filter pressing; the finer the particle size, the more difficult the removal of water becomes.

A wide range of driers is used by the industry although the two most common types are still the rotary and Buell. The rotary drier typically reduces the moisture content of filter cake from about 30 per cent to 10 per cent. The Buell drier, which is also capable of reducing moisture to 10 per cent, contains a system of circular shelving for carrying shredded clay which is transferred from shelf to shelf by scraper arms. Band driers and fluidised bed driers have also been introduced and direct attritor

mills are used as required to reduce the moisture content of the clay from the driers to 1 per cent.

Calcination

Specially selected kaolin with high alumina and low iron and alkali contents undergoes high temperature calcination to produce a refractory chamotte.

Selected kaolin slurry is initially reduced to a moisture content of about 35 per cent by low pressure filter pressing. The shredded filter cake is then dried, pelletised and extruded into briquettes with a moisture content of around 20 per cent. The briquettes are automatically stacked on kiln cars to give uniform heat penetration and dried to about 1 per cent moisture in a tunnel drier. High temperature calcination is carried out in a tunnel kiln, with a firing cycle of 44 hours and a maximum temperature of 1530°C. Following calcination the briquettes are fed to a crushing, milling and grading plant which delivers a range of sized products.

The refractory chamotte, known as 'Molochite', consists of a mixture of mullite ($Al_2O_3.SiO_2$) needles set in an amorphous silica glass in the proportions 56 per cent and 44 per cent respectively. The absence of crystalline silica in its cristobalite form results from the high alkali content of the clay which assists glass formation and ensures a low and uniform thermal expansion. Typical alumina, iron oxide and total alkalis contents are 42-43 per cent Al_2O_3; 0.75 per cent Fe_2O_3 and 1.5 to 2 per cent $K_2O + Na_2O$, with a pyrometric cone equivalent of 35 (1770°C).

Low temperature calcination of kaolin is also carried out at Lee Moor in Devon to produce a range of products for use as fillers in paint, rubber and plastics. Selected clays of fine particle size (80 per cent <2 μm) and high brightness are used as feedstock and calcined in a multi-hearth Herreschoff calciner. Temperature and passage through the calciner are strictly controlled to produce three different products. Typical firing temperatures, depending on the application of the filler, are 1130°C for paint; 1080°C for rubber products and 850°C for plastics, the lower temperature in the latter case prevents the loss of insulation properties which are important in PVC insulating cables. Dehydroxylation of kaolinite occurs at 500°-600°C with the formation of meta-kaolinite. Above 900°C meta-kaolinite changes to silicon spinel and subsequently, at over 1100°C, to mullite and free silica. In contrast to 'Molochite', mullite formation does not take place. Calcination also results in up to a four point improvement in ISO brightness to about 91 in the case of calcined clay for use in paint. Somewhat lower brightness clays can be utilised for rubber and plastics. Thermal treatment also significantly increases the abrasiveness of kaolin. The high alkali content of English clays, compared with, for example, Georgia kaolins makes the calcined clay more prone to glass formation with a consequent increase in abrasiveness rendering them unsuitable as a paper filler.

Transport

Whilst the kaolin deposits of Southwest England are conveniently situated with respect to ports serving the important export market and representing over 80 per cent of sales, they are, nevertheless, comparatively remote from the main industrial centres in the United Kingdom. The home market is principally served by road and rail (Table 7), the use of coastal shipping to paper manufacturing plant having declined appreciably during the last decade.

Table 7 Sales of kaolin (ECC) from mid-Cornwall to the UK market, 1979

| Mode of distribution | Product form (tonnes) | | Total |
	Bulk	Bagged	
Road	110,000	71,000	181,000
Rail	121,000	26,000	147,000
Sea	13,000	Nil	13,000
Total	244,000	97,000	341,000

Source: Pearce, 1981. *Ind.Miner.Lond.,* 1981, March Supplement, p. 43.

The flexibility of road service has still many advantages over rail transport except for very long distance journeys or where suitable railhead depots are available.

Kaolin exports from Cornwall are principally through the ports of Par and Fowey, only very minor shipments now being made through Charlestown. Exports from Devon are mainly through Plymouth. Par is a tidal port owned by English China Clays and is capable of handling cargoes of up to 1500 tonnes dead weight. Bulk train loads are, however, also dispatched to Europe.

Fowey is an estuarine port leased by English China Clays from British Rail and is capable of allowing clay shipments of up to 10,500 tonnes. The two ports are linked by a private road and clay to Fowey is carried both by road and rail. A proportion of the clay traffic to Par is by slurry pipeline and dockside drying facilities are available at the harbour. Some 2 million tonnes a year pass through the ports of Par and Fowey mostly in lump bulk form (Pearce, 1981).

In its major applications in the paper and ceramic industries, kaolin is utilised in a wet process. There is, therefore, increasing interest being shown in the transport of clay in slurry form. Clay slurries of approximately 70 per cent solids, 300 centipoise and 1.7 g cm^{-3} density have been transported to the home market by road and rail for many years. Slurry transport has been extended to ships and regular cargoes of 1,500 slurry tonnes are now shipped to Western Europe. There has been a substantial increase in this form of traffic since the service was introduced in 1978.

Land Use

The extraction of kaolin in Cornwall and Devon, whilst confined to well defined areas, has a major visual impact. Very large tonnages of rock waste (about 20 million tonnes a year), representing over 80 per cent of the material extracted in the form of overburden, stent, coarse sand and micaceous residues, are an unavoidable by-product of both kaolin mining and processing and are well recognised as being the most intrusive element on the environment. Large voids are thus created by kaolin mining, some of which are used for water storage by the industry, but, since kaolinisation continues in depth, only selected backfilling has been possible to prevent sterilisation of resources. Large areas are therefore required for waste disposal.

The planning authorities of Cornwall and Devon recognise the importance of the industry both locally, providing direct and indirect employment, and nationally as a major exporter. In recognition of this, the respective Structure Plans contain policies aimed at safeguarding resources of clay against sterilisation by other forms of land use development (Cornwall County Council, 1981; Devon County Council, 1981). However, the authorities will, by agreement, ensure that waste disposal arrangements have the least environmental impact and will support the industry in continuing to explore every possibility for making the fullest commercial use of sand and other waste products.

As a building sand or fine aggregate for concrete, waste sand can be processed to the appropriate British Standard specification. However, investigations have shown that the presence of mica and the angularity of the quartz do impose some penalties in concrete strength and workability (Gutt et al, 1974). For a wide range of road construction applications, however, the mica content of the sand does not pose any serious engineering problems (Tubey, 1978). A number of market studies have been undertaken (eg Cooper, 1975) on utilising the waste sand but transport costs have, as yet, precluded the large scale marketing of the sand for construction purposes outside the immediate area of operations.

The County Councils also intend to ensure that landscaping is used to best effect so as to minimise the visual impact of kaolin extraction and, particularly, waste disposal. In the past decade considerable advances have been made in this direction with the grassing over of some of the waste tips and their use as open pastures for sheep (Allaby, 1983).

In 1948 the then Board of Trade produced a Report on China Clay which recommended the preparation of a long-term development plan for the industry. Consequently, in 1949 the China Clay Standing Conference was constituted by the then Minister of Town and Country Planning to co-ordinate the views of the local planning authorities, the industry and other interested bodies on such matters as development plan provision for kaolin working, waste disposal and problems connected with the granting of planning permissions. The China Clay Standing Conference Report

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was published in 1955 and amongst its conclusions and recommendations it defined both the extent of clay resources and also 'Consultation Areas', including land for ancillary purposes, so as to prevent sterilisation of valuable resources by other forms of development. However, kaolin production has grown substantially since then and the industry has become increasingly capital intensive. Thus long term planning has involved consideration of factors, both economic and relating to land requirements, which have assumed an increased importance in recent years.

In the St Austell area extensions to the original Consultation Area were subsequently made and in 1966 it was recommended by the then Minister of Housing and Local Government that a 50 year plan be prepared by the industry indicating the provisions which would be necessary to allow for development over that period. A plan covering the St Austell China Clay Area was prepared and formed the basis of discussions, principally between the industry and local planning authorities. However, because of changing technology and variations in demand, it was recognised that a detailed plan showing progressive developments over 50 years was not practicable and that the plan should, therefore, be more flexible and subject to periodic review. The resulting study was published in 1972 and, following consultations and amendments, a report incorporating a Short Term Plan and Long Term Strategy was published in 1974 (Cornwall County Council, 1974).

This report provides details of the total land requirements for pits, plant areas and waste disposal for a period of approximately 50 years from the early 1970s. This is the Long Term strategy. The anticipated pit development in the St Austell Granite during this period is shown in Fig 7. Total land requirements for pit development were estimated at 2,510 hectares and for waste disposal 3,930 hectares. In view of the decrease in growth in demand for kaolin in recent years, the need for a flexible approach to long term planning for the industry is vindicated. The Short Term Development Plan in the report has now been superseded by the Short Term Development Plan for 1977-84 (Cornwall County Council, 1979), which provides details of anticipated land requirements up to 1984. Of the forecast land requirement of 430 hectares the major part is required for waste disposal. Within the St Austell China Clay Area a number of 'island settlements' have been protected from kaolin working and waste disposal.

Current consents on Bodmin Moor contain sufficient reserves to extend workings for a further 30 years.

There is a long term commitment to the working of kaolin in the Lee Moor and Crownhill Down areas of Devon. Current planning consents for kaolin extraction exceed 50 years output, although areas allocated for tipping are considerably less. Current planning consents for kaolin extraction, waste disposal and the location of ancillary plant cover 1,400 hectares, of which 412 hectares are within the Dartmoor National Park.

Demand

The paper industry is by far the largest market for kaolin, accounting for some 65 to 70 per cent of total Western European consumption, and it is impossible to envisage any future use of kaolin that might approach it in importance. There is, therefore, a very close relationship between kaolin demand and the performance of the paper industry, which itself has long been recognised as reflecting GNP levels, although accentuating the peaks and troughs in the normal economic cycle (Clark, 1977). The dependence of the United Kingdom kaolin industry on Western European paper manufacture is very pronounced with some 80 per cent of total production being sold for this purpose. As a result, the largest producer, English China Clays (ECC), which supplies Western European paper manufacturers with about 70 per cent of their coating clays and over 50 per cent of their filler clays, carries out regular surveys of printing and writing paper consumption which accounts for some 90 per cent of total kaolin consumption in the paper industry (Anon, 1982b). The company consider that economic activity measured by GNP is the most important single factor in the consumption of printing and writing paper.

Wood pulp for the manufacture of printing and writing paper may be of two varieties; mechanical, which is prepared by crushing and grinding wood, and woodfree, produced by chemically treating the wood. Since kaolin is used as a filler in both varieties, printing and writing paper can be divided into four categories; coated mechanical, uncoated mechanical, coated woodfree and uncoated woodfree.

Western European printing and writing paper production in 1980 was 12.92 million tonnes and ECC estimate that this will increase to 14.76 million tonnes by 1985. The increase is more modest than previous years which, the company suggests, implies the onset of market saturation. Of the various categories of paper, however, coated varieties have shown faster growth rates in consumption than uncoated varieties, resulting in a greater consumption of coating clays than filler clays, a reversal of the trend in the mid-1970s (Table 8). Coating allows the use of cheaper mechanical papers at the expense of higher priced woodfree grades. However, an increasing share of the paper coating market is being taken by calcium carbonates and, although production is still comparatively modest, growth in output is significant. The extent to which future consumption of paper may be affected, either adversely or otherwise, by the wider use of computer technology in the communications field (Videotex) is as yet not clear.

Papermaking is also the main UK market for kaolin but the ceramics industry, particularly whiteware pottery manufacture, is also a major outlet. In addition, significant quantities of clay are used in paints, plastics, rubber, glass fibre, white cement and as an anti-caking agent in fertilisers. Apparent consumption of kaolin in the United Kingdom during the post-war period is shown in Fig 12. Consumption peaked during the 1960s and has since declined significantly reflecting principally
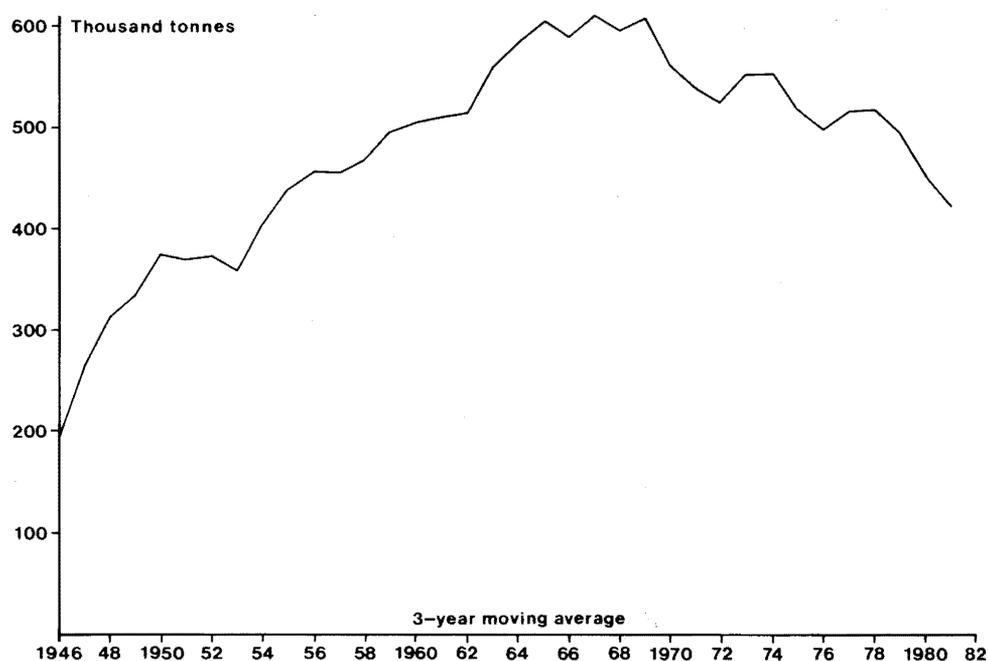
Table 8   Western European kaolin consumption, 1978-1981

	1978		1979		1980		1981	
	Mt	*%*	*Mt*	*%*	*Mt*	*%*	*Mt*	*%*
Paper coating	1.4	30	1.6	34	1.6	36	1.6	36
Paper filling	1.4	30	1.4	30	1.3	29	1.3	29
Ceramics (a)	1.2	26	1.1	23	1.0	22	1.0	22
PRP (b)	0.4	9	0.4	9	0.35	8	0.35	8
Others	0.2	5	0.2	4	0.2	5	0.2	5
Total	4.6	100	4.7	100	4.45	100	4.45	100

(a) Includes refractories, white cement and glass fibre
(b) Paint, rubber and plastics.

Source: Watson, 1982.

Fig 12   United Kingdom: Kaolin consumption, 1946-1982.
(Based on Humphreys and Briggs, 1983).

Table 9   United Kingdom: Printing and writing paper production 1964-1982

Thousand Tonnes

1964	1,533	1974	1,208
1965	1,127	1975	893
1966	1,177	1976	979
1967	1,178	1977	991
1969	1,228	1978	1,059
1970	1,225	1979	1,057
1971	1,053	1980	963
1972	1,100	1981	920
1973	1,196	1982	857

Source: British Paper and Board Federation

the decrease in printing and writing paper production (*see* Table 9). This has been particularly marked during recent years due to economic factors relating to severe overseas competition. The pottery industry has also suffered from increased competition in overseas markets and from the current recession.

Prices

Prices for kaolin are regularly published by the journal 'Industrial Minerals'; figures quoted for December 1983 being as follows:—

Principal grades, refined, bulk FOB a tonne.

Coating clays	£60-£110
Filler clays	£25-£60
Pottery clays	£25-£65

The range of values reflect the range of grades available, bulk clay generally being sold on a 10 per cent moisture basis. Dried (1 per cent moisture), powdered and bagged clay is appreciably more costly. Powdered and bagged pharmaceutical grades of clay range up to £200 a tonne for Light Kaolin. Calcined grades of clay generally fall within the range £170 to £200 a tonne.

The unit value of United Kingdom kaolin exports has remained relatively stable in constant prices from the end of the Second World War to the late 1960s. However, during the last decade or so average export values have increased from £38.4/tonne in 1967 to £49.8/tonne in 1980 (in 1980 constant prices) reflecting the trend towards the production of a larger proportion of value-added, higher quality clays.

Production

The kaolin deposits of Southwest England are a major mineral resource and support an industry of national and international importance. Kaolin production began in the mid-18th century and it is estimated that total output up to and including 1982 has been some 110 million tonnes. The value of production, estimated at £135 million in 1982, makes kaolin by far the most important non-energy mineral produced in the United Kingdom, excluding the main construction minerals. Output represents some 12 per cent of the total value of non-energy mineral production. Production during the period 1855 to 1982 is shown in Fig 13, the marked impact on output of the two World Wars being well illustrated. Sales of kaolin by UK companies during the period 1960 to 1982 are shown in Table 10.

The world economic recession, particularly its affect on Western Europe, has resulted in a significant decrease in sales in recent years and it is conceivable that the zenith of kaolin production in the United Kingdom has already been achieved.
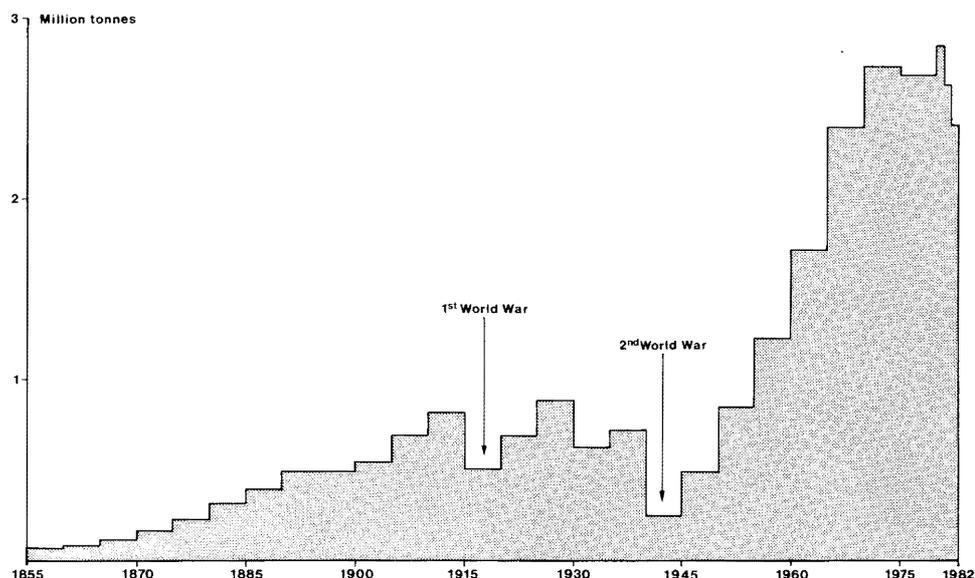
Fig 13   United Kingdom: Kaolin production, 1855-1982.

Table 10   United Kingdom: Sales of China Clay, 1960-1982

Thousand Tonnes		Thousand Tonnes	
1960	1,558	1972	2,573
1961	1,625	1973	2,966
1962	1,621	1974	3,023
1963	1,825	1975	2,266
1964	2,007	1976	2,533
1965	2,083	1977	2,775
1966	2,354	1978	2,859
1967	2,366	1979	3,102
1968	2,515	1980	2,839
1969	2,702	1981	2,629
1970	2,787	1982	2,421
1971	2,420		

Source: China Clay Association

The United Kingdom was the world's largest producer of kaolin until the Second World War when it was surpassed by the USA. In 1981 these two countries contributed 15 and 40 per cent respectively to total world production. The major world producers are shown in Table 11. There are a large number of other producing countries with China and the German Democratic Republic being among the more important. Comparison of individual country production data is difficult because figures do not always refer to refined production and may include both partly beneficiated material and lower quality clays.
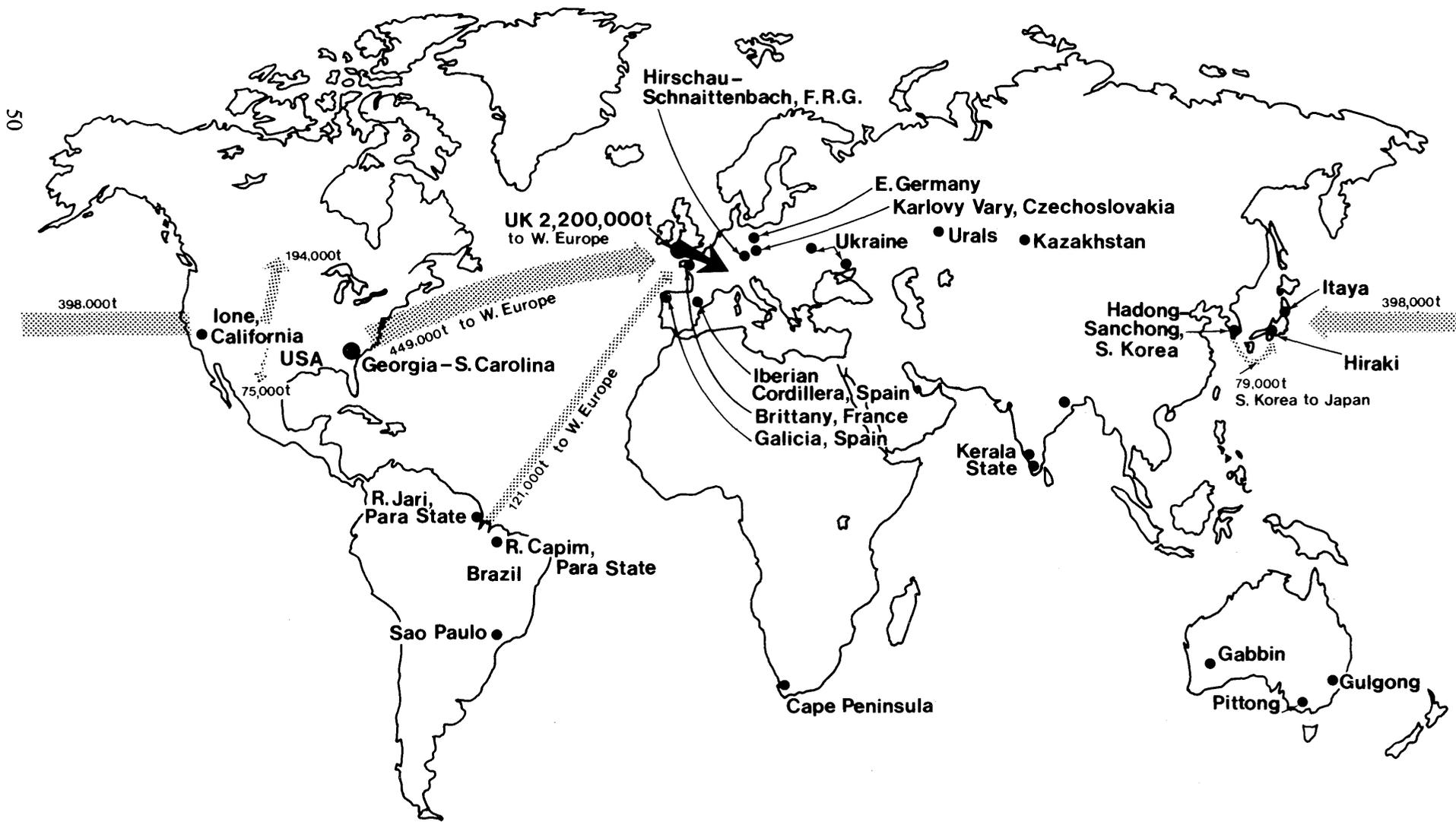
Fig 14   Location of major world kaolin production and main trade in kaolin

Table 11 Major World Producers of Kaolin, 1977-1981

Country		Thousand Tonnes					
		1977	1978	1979	1980	1981	1982
USA	(a)	5,861	6,326	7,040	7,148	6,949	5,700(b)
United Kingdom	(a)	2,775	2,859	3,102	2,839	2,629	2,421
Soviet Union	(b)	2,300	2,400	2,500	2,500	2,500	2,500
Czechoslovakia	(c)	580	499	513	518	508	527
India	(c)	445	416	489	460	509	558
Germany, FR		399	413	432	367	371	377
Brazil		260	294	349	410	470	418
France	(d)	579	265	315	338	403	347
Korea, Republic of		357	366	374	274	225	175
Japan		203	228	162	170	154	150
Other Countries		2,150	2,340	2,490	2,580	2,510	2,650
Total		15,900	16,400	17,800	17,700	17,200	15,850

(a) Sales
(b) Estimated
(c) Partly beneficiated
(d) Including kaolinitic clay

Source: British Geological Survey.

World production of paper coating clays, which has been estimated at about 4.5 million tonnes, is dominated by the USA and United Kingdom, although in recent years Brazil has also emerged as a significant producer. Only minor quantities are produced elsewhere. Production of ceramic and filler grades is much more widespread (see Fig 14). A brief review of some of the major producing countries is given below.

USA

The Atlantic Coastal Plain in southeastern USA is the major world source of kaolin with Georgia and South Carolina accounting for some 78 and 11 per cent respectively of total US production. The deposits occur in a southwest-northeast trending belt extending nearly 250 km along the northwestern edge of the Coastal Plain and dip very gently seawards. Economically important deposits occur as lenses and tabular layers up to 20 m thick and covering several kilometres, and are present at two stratigraphical levels, firstly within the Huber Formation of Upper Palaeocene to Middle Eocene age and also at or near the top of Upper Cretaceous strata. The deposits are of a high purity, containing over 80 per cent clay as dug, and consist predominantly of kaolinite, although nacrite is nearly always present and in a few places occurs in significant amounts (Hurst, *et al*, 1979).

Typically, the Cretaceous kaolins are soft and of a high purity, although with 60-65 per cent <2 μm they are somewhat coarser than the Tertiary kaolins. The deposits occur mainly in siliceous clastic sediments and may stratigraphically overlie one another. They often exhibit eroded upper surfaces, indicating that the deposits have been subjected to reworking, and associated thin bauxitic layers are indicative of intense lateritic weathering.

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The finer-grained (90 per cent <2 μm), hard Tertiary kaolins occur at or near the top of the Huber Formation, which consists mainly of sand, kaolinitic sands and kaolin. Evidence of reworking is indicated by the presence of an eroded upper surface which has also been extensively burrowed.

The Cretaceous deposits are believed to have been formed by the intense weathering of aluminous sediments originally derived from the crystalline rocks of the Piedmont to the northwest. The deposits, therefore, represent the uneroded remnants of the pallid zone of lateritic weathering profiles and, also, reworked, winnowed and redeposited material derived from these profiles. The Tertiary kaolins were derived predominantly from the erosion of pre-existing Cretaceous deposits although they also have been subject to subsequent lateritic weathering (Hurst, *et al*, 1979).

The horizontally bedded nature of the deposits allows them to be worked by conventional opencast mining methods. The introduction of new processing techniques, such as high intensity magnetic separation, has made possible significant improvements in the brightness of the clays and, as a result, considerably increased recoverable reserves. Kaolin resources in Georgia are placed at between 5 and 10 billion (10^9) tonnes by the US Bureau of Mines.

Production has been greatly increased during the last two decades, principally in response to the demands of the home market. US sales of kaolin increased from 2.5 million tonnes in 1960 to 6.95 million tonnes in 1981, an average annual growth rate of 5.2 per cent. The comparable growth rate for United Kingdom sales over the same period was 2.4 per cent. US exports of kaolin have increased even more rapidly, from 73,000 tonnes in 1960 to nearly 1.3 million tonnes in 1981, an average growth rate of some 14 per cent a year. However, US kaolin production showed a marked decline in 1982 to 5.7 million tonnes, although exports remained at a high level at nearly 1.2 million tonnes.

Brazil

In recent years Brazil has emerged as a major world producer of kaolin and particularly as an important source of coating clays which are mainly exported to the European market. Major production of coating clays is based on deposits near Monte Dourado on the River Jari, Para state, some 100 km upstream from its confluence with the Amazon. Thick and extensive kaolin deposits, which came into production in 1976, are developed in the Belterra Clay at the top of the Pliocene Barreiras Series beneath a lateritic zone and are thought to have been derived from *in situ* alteration of arkosic sands (Murray and Partridge, 1982). Large resources of kaolin, associated with an extensive peneplane and occurring beneath very large bauxite deposits, have also been discovered in the middle reaches of the River Capim, also in Para state. The kaolin, which was also formed by the weathering of sediments of the Barreiras Series, has a high brightness and low viscosity and appears to be suitable for paper coating.

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Residual kaolin deposits developed on Precambrian granitic gneiss and migmatites are also worked for local ceramic and paper coating purposes at the Mogi das Cruzes deposit near Sao Paulo. The rock has been weathered to a depth of at least 40 m and the clay is extracted by hydraulic mining and beneficiated by hydrocyclones. Current production is about 60,000 tonnes a year (Wilson and Souza Santos, 1982).

Federal Republic of Germany

Outside the United Kingdom, the Federal Republic of Germany is the leading producer of kaolin in Western Europe. European deposits are smaller than those in the United Kingdom and of lower quality, the clays being used mainly for filler and ceramic applications and are generally unsuitable for paper coating.

The kaolin deposits of the Federal Republic of Germany are associated with the weathering of acid igneous and sedimentary rocks. The most important deposits occur between Hirschau and Schnaittenbach in Bavaria where a sequence of K-feldspar-bearing Lower Triassic arkoses and arkosic sandstones were partially kaolinised *in situ* by circulating groundwater soon after deposition. The kaolin is mainly worked for paper filling and fine ceramics with silica sand and feldspar as by-products. Kaolin for whiteware ceramic and paper manufacture is also exploited from kaolinised granites south of Tirschenreath, also in Bavaria.

France

Brittany is the major source of kaolin in France and supplies some 75 per cent of the country's output. A number of small deposits, developed on Variscan granites and Precambrian metamorphic rocks, are worked near Ploëmeur, Berrien and Quessoy. The deposits, which have kaolin contents in the range 25 to 45 per cent, are not dissimilar to those in Devon and Cornwall but are considered to be related principally to weathering action (Esteoule-Choux, 1983). The kaolin is used mainly in ceramics and for filler applications.

Czechoslovakia

Czechoslovakia is a major producer of kaolin, also exporting substantial quantities of filler grade clays to other European countries. In 1981 some 225,000 tonnes were exported to Western Europe with the Federal Republic of Germany being the main market. The most important deposits occur in the Karlovy Vary area of the Bohemian Massif in the extreme northwestern part of the country. Here, Variscan granites are believed to have been affected by deep weathering and are kaolinised to a depth of 50 m, although only some 20 m to 30 m is generally worked. Similar residual deposits on granites and gneisses also occur near Znojmo in southern Moravia. Near Plzeň and Podbořany in western Bohemia

sedimentary kaolins occur associated with Carboniferous clastic sediments. Water-washed kaolins are produced in Czechoslovakia principally for filler and ceramic use (Kuzvart, 1969).

USSR

Kaolin is produced in the Ukraine, the main source of the mineral in the Soviet Union, and also in the Urals and Kazakhstan (Petrov and Chukhrov, 1977). Deposits are associated with an extensive weathering mantle of early Mesozoic age which may extend to depths of 50 m and 80 m, particularly where associated with fault zones. Clay quality is dependent on the mineralogy of the parent rock and commercially important deposits are, therefore, generally developed on low-iron host rocks such as Precambrian granites and muscovite schists.

Democratic Republic of Germany

A roughly east-west belt of kaolin deposits occurs in the southern part of the country along the northern margins of the Central Highlands of Sachsen and Thuringen. The most important deposits are at Kemmlitz, Caminau, Spergau, Seilitz and Moderau-Morl (Storr et al, 1977). Kaolinisation is believed to have resulted from weathering processes and individual deposits are developed on acid volcanic and plutonic rocks and arkoses, generally to depths of 10 to 30 m but rarely exceeding 50 m.

Spain

The most important kaolin deposits in Spain are of two main types; the sedimentary kaolinitic sands of the central-eastern region (the Iberian Cordillera) and the primary deposits developed on granitic host rocks in Galicia in northwest Spain (Vivaldi, 1969). Sedimentary deposits, consisting of kaolinitic sands with an average kaolin content of some 10 per cent, are worked in the provinces of Guadalajara, Valencia and Cuenca for ceramic and paper filling applications, although some kaolin is also produced for coating purposes. The kaolin-bearing sands occur as alternating beds up to 10 to 20 m in thickness in continental Cretaceous sediments referred to the Wealden (Lower Cretaceous) and Utrillas (Albian) formations. Despite their lower kaolinite content these kaolins are whiter and finer than the primary deposits in Galicia. The kaolin deposits in the provinces of Lugo and La Coruna in Galicia are associated with faulting and zones of mylonitisation and are believed to be essentially of hydrothermal origin. Kaolinised zones over 50 m thick have been proved although usually only some 20 to 30 m is worked. Typical kaolin contents are in the range 20 to 30 per cent and the clay is again used in ceramics and paper filling. The erosion of primary deposits has produced sedimentary kaolin deposits up to 10 to 12 m thick of both Tertiary and Quaternary age.

South Africa

Primary kaolins occur in Western Cape region, Namaqualand and Natal, although only the deposits in Western Cape Region are currently exploited (Murray and Heckroodt, 1979). The deposits were formed by the weathering of the Proterozoic Cape granite and typically have high kaolin yields of up to 50 per cent. However, the presence of a mixed-layer smectite-illite clay mineral adversely affects the rheological properties of the clay, making it unsuitable for paper coating, although it is acceptable for paper filling and ceramic applications. Production is small.

India

Kaolin deposits in India are widespread. Clays produced in the Cannanore, Quilon and Trivandrum districts of Kerala state are generally recognised as being of the highest quality and are extensively used in the paint, textile, paper, rubber, ceramic and pharmaceutical industries. The deposits are of both residual and sedimentary origin, the former having developed on Precambrian granites and the latter being of Tertiary age. Elsewhere, good quality processed kaolin is produced in the Bhagalpur and Singhbhum districts of Bihar state, the Mayurbhanj district of Orissa, the Birbhum district of West Bengal and the Sabarkantha district of Gujarat.

Republic of South Korea

Large scale extraction of kaolin is confined to the Hadong-Sanchong district in southern Korea where halloysitic clays, formed by the *in situ* weathering of anorthosite and Precambrian feldspathic gneisses, are developed. The clays are of variable grade with appreciable staining by iron oxides in places. Halloysite is used by the domestic ceramics industry but some 30 per cent is exported, principally to Japan.

Japan

Most of the kaolin-rich clays in Japan are of hydrothermal origin due to the alteration of Cretaceous and Plio-Pleistocene volcanics. The deposits are generally of variable mineralogical and chemical composition and are also of irregular shape and extent. Important deposits occur in Itaya in northeast Honshu, Hiraki in western Honshu and Iriki in southern Kyushu, the clays being used in paper and for ceramic applications. Halloysitic deposits, also of hydrothermal origin, are similarly worked for use in paper filling (Fujii, 1981). The absence of high quality deposits makes Japan a major importer of kaolin.

Australia

Most of the kaolin deposits of Australia are of residual origin related to a period of intense lateritic weathering in early Tertiary times, the kaolin

now representing the pallid zone of this lateritic profile (Gaskin *et al*, 1979). Reworking of residual clays has produced a number of sedimentary kaolin deposits, although none are extensive or of high quality. Kaolin production is mainly confined to Victoria and New South Wales, although production from the Gabbin deposit in Western Australia was scheduled to start in 1982. Production of paper coating kaolin is confined to the Pittong deposit some 130 km northwest of Melbourne. The kaolinisation at Pittong is associated with the deep Tertiary weathering of Devonian granites, alteration extending to depths of 40 m. Similar deposits also occur at Lal Lal near Ballarat in Victoria. In New South Wales the highest quality deposits are of sedimentary origin derived locally from kaolinised granite (Baker and Uren, 1982). The most important deposits are in the Gulgong-Home Rule-Stubbs area, some 300 km northwest of Sydney.

At Gabbin, in Western Australia, kaolinisation extends to depths of up to 50 m in a primary deposit developed on weathered granite. The kaolin has a high brightness and low viscosity and is suitable for paper coating (Walker, 1978). Kaolin underlying the Weipa bauxite deposits in northern Queensland is now being mined and processed.

Other countries

Kaolin is produced in a large number of other countries. China is a major producer and significant amounts are also produced in Argentina and Indonesia.

Overseas Trade

Exports (and imports) of kaolin are recorded by the United Kingdom Tariff and Overseas Classification for 1982 under the following headings:— 2507 1100—'Crude kaolin clay' and 2507 1900—'Kaolin clay other than crude'. Virtually all trade appears under the latter heading which refers to refined clays.

Until the advent of North Sea oil, kaolin was for many years the United Kingdom's most important mineral export. Kaolin still dominates non-energy mineral exports and makes a very substantial contribution to the balance of payments (Fig 15).

The United Kingdom is by far the world's largest exporter of kaolin, a position it has held for many years. Typically, over 80 per cent of United Kingdom production is exported (*see* Fig 15) and in 1981 exports of 2.2 million tonnes accounted for nearly 50 per cent of world trade in kaolin. In comparison, exports of kaolin by the USA, the second largest exporter, were 1.3 million tonnes in 1981. United Kingdom exports of kaolin by major country of destination is shown in Table 12.
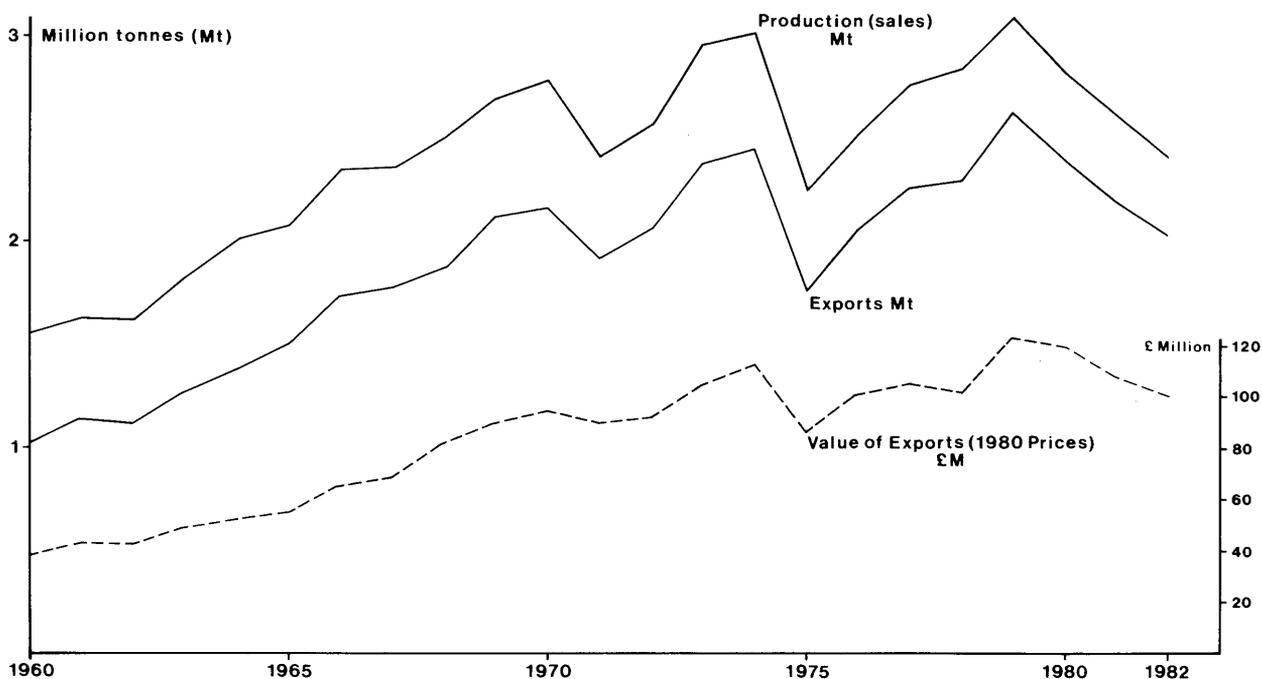
Fig 15 United Kingdom: Kaolin sales and exports, 1960-1982

Table 12 United Kingdom: Exports of kaolin by major countries of destination, 1978-1982

Country of destination	1978	Tonnes 1979	1980	1982	Value 1982 (£ thousand)
Germany, F.R.	401,511	467,749	461,448	425,572	21,948
Finland	316,798	388,730	348,679	331,004	20,244
Italy	306,394	346,472	321,502	230,787	11,240
Sweden	237,517	265,590	236,760	251,090	14,216
France	230,810	242,163	239,840	211,497	12,069
Netherlands	161,033	180,904	175,392	161,757	9,557
Belgium-Luxembourg	116,605	130,037	117,542	121,403	5,710
Spain	104,488	117,960	99,012	95,405	6,034
Norway	76,857	81,265	75,833	72,018	3,364
Poland	72,736	92,025	49,588	3,683	346
Switzerland	38,575	51,947	49,991	50,741	3,309
USA	40,456	63,170	22,590	12,105	666
Other countries	199,733	200,225	204,223	138,691	9,643
Total	2,303,513	2,628,237	2,402,400	2,105,753	118,346

Source: HM Customs and Excise.

Data for 1981 are considered unreliable and are not therefore reproduced. Total United Kingdom exports of kaolin in 1983 were 2.15 million tonnes valued at £122.7 million.

Almost all United Kingdom exports of kaolin are to Western Europe. Formerly a significant proportion was destined for North America but,

with the emergence of the USA as a major producer, exports have steadily declined (Table 13).

Table 13   United Kingdom: Post-war exports of kaolin by region of destination, indicating post-war trends

Area	1952		1962		1972		1982	
	000t	%	000t	%	000t	%	000t	%
EEC	207	44.4	621	55.5	1,197	57.8	1,194	56.7
Other Western Europe	103	22.1	301	26.9	686	33.1	830	39.3
North America	138	29.6	135	12.1	66	3.2	12	0.7
Other countries	18	3.9	61	5.5	123	5.9	70	3.3
Total	466	100	1,118	100	2,072	100	2,106	100

Note: EEC figures apply to the current members of the Community.
Source: HM Customs and Excise

United Kingdom imports of kaolin are negligible and never exceed 10,000 tonnes a year. The major proportion of imports are from Australia and the USA. Major world trade flows in kaolin exports are shown in Fig 14, which highlights the importance of the Western European market and the competition faced by the United Kingdom from the USA and Brazil.

Industry

There are four kaolin producers in the United Kingdom; English Clays Lovering Pochin and Co Ltd (capacity 3 million tonnes), Watts Blake Bearne and Co PLC (120,000 tonnes), The Goonvean and Rostowrack China Clay Co Ltd (100,000 tonnes), and Steetley Minerals Ltd (80,000 tonnes).

English Clays Lovering Pochin and Co Ltd (ECLP), is a subsidiary of English China Clays PLC (ECC). ECC was incorporated in 1919 by the merger of the then three largest producers which began the much needed rationalisation of the industry (there were seventy individual producers in 1914). This continued as ECC absorbed other producers throughout the 1920s. The final major merger with Lovering China Clays Ltd and H D Pochin & Co Ltd, to form ECLP, took place in 1932 (Hudson, 1969). Today ECLP, which dominates United Kingdom production and accounts for over 90 per cent of sales, is the world's largest producer and exporter of kaolin. The company has operations in the St Austell, Dartmoor, Bodmin Moor and Land's End granites. Subsidiaries of ECC involved in kaolin extraction are Anglo-American Clays Corporation, which produces high quality kaolin and calcined clay from sedimentary deposits in Georgia, USA; Kaolin Australia Pty Ltd, Pittong, Victoria, Australia; Société des Kaolins du Finistère SA, Brittany, France and ECC do Brasil.

Associated overseas companies include English Indian Clays Ltd, producing filler, ceramic and some coating clays in Kerala state, India; Cia Espanola de Caolines SA engaged in a project to produce filler,

ceramic and coating clays in Guadalajara province, Spain; and Cia Anglo-Portuguesa de Caolinos Sarl, with a similar project at Viana do Castelo in Portugal.

The major part of the kaolin output of Watts Blake Bearne and Co PLC goes to the ceramics industry with which it has close contacts, arising from its major role as the world's leading producer of ball clay. The company operates two kaolin pits in Devon, where they have been active for over 100 years; at Heddon on the Crownhill Down Granite and Shaugh Moor in the Lee Moor area within the main Dartmoor Granite.

Steetley Minerals Ltd, an operating subsidiary of Steetley plc, operates two pits, Greensplat and Bodelva, both within the St. Austell Granite, and supplies paper filler clays principally to the West German market. The company's interests in kaolin were partially inherited through Berk Ltd, which acquired Greensplat China Clay Ltd in 1960 and was subsequently bought by Steetley in 1971. Bodelva pit was acquired from Engelhard Minerals in 1973, having formerly belonged to the Inveresk Paper Group.

The Goonvean and Rostowrack China Clay Co. Ltd is a private independent producer formed in 1931 to exploit the china clay and china stone resources on land owned by the Falmouth family. The company produces a range of high quality paper filler, ceramic and speciality clays, the major proportion being sold as filler clays to the paper industry. The company operates three pits, Goonvean, Rostowrack and Great Wheal Prosper, all within the St Austell Granite, and is the sole UK producer of china stone.

The producers are all members of The China Clay Association, a trade association which represents and promotes the interests of the industry. The China Clay Council is a voluntary organisation set up in 1950 by an Agreement between employers and the Transport and General Workers Union.

The Chairman and an independent member are appointed by the Secretary of State for Trade and Industry and six members are nominated by the employers and six by the trade unions. An official of the Department of Trade and Industry is an observer. The Council may look into almost any aspect of the industry and its main terms of reference are to advise on methods designed to increase efficiency and productivity in the industry.

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