Clay and clay materials in South Africa*

by R. O. HECKROODT†

SYNOPSIS
After a brief review of the characteristics of clay minerals and their origin, a summary is given of the industrial uses of different types of clay materials. The mining and beneficiation of clays are discussed, with special reference to the upgrading of certain types of clays.

The occurrence and resources of the more important varieties of clays are dealt with in some detail, viz. residual kaolins derived from granite and sediments, brickmaking clays, refractory clays, bentonite, and palygorskite.

The Republic of South Africa is well endowed with a wide spectrum of clay materials, with one important exception. Kaolins suitable for paper coating is not known to occur in the Republic, and efforts to beneficiate and treat local materials to achieve the desired properties have so far been unsuccessful.

INTRODUCTION
It is difficult to define the term clay, because its attributes differ for various disciplines. As a geological term, it is used for a variety of materials, some of which may not possess all these attributes. In the context of this review, clay is defined in a general way as an earthy substance containing a mixture of hydrous aluminium silicates (the clay minerals), with residual fragments of other minerals and colloidal matter; it possesses the property of plasticity when wet, but becomes permanently hard when fired to a high temperature.

Furthermore, the term clay is used for materials that have been formed by weathering processes, or are the result of hydrothermal action, or have been deposited as a sediment. It also denotes the finest fraction of a sediment or soil in the classification of clay, silt and sand. The particles of most clay minerals are very small, and it is only rarely that their 'equivalent' size exceeds 2 μm. On the other hand, the particles of non-clay minerals are usually not smaller than about 1 to 2 μm, and most disciplines thus place the upper limit of the clay fraction at 2 μm since this particle size seems to be the natural division between the clay and the non-clay minerals.

Clay materials are used in the manufacture of a large variety of products such as ceramics, paper, polymers, paint, and many others. In all of these applications, clay materials play a vital and irreplaceable role. They are sometimes used as active ingredients, where they contribute to the chemical and physical requirements of the product, such as in ceramic bodies and glass. They are also used as inactive ingredients or fillers in plastics and paints, where their main function is to dilute or extend the product. Clays can operate as agents in many processes such as water purification, and they are raw materials from which aluminium can be extracted.

This review is presented in two parts: Part I deals with the clay minerals, the origin of clays, the classification of clay materials, the industrial uses of clays and the upgrading of beneficiated materials; Part II details the occurrences and resources of clay materials in South Africa. These two parts are followed by a list of references and a bibliography that are relevant to both parts.

The subject is very wide-ranging and, in the first instance, the reader is referred to the two general works listed in the bibliography. More detailed published information on specific topics is referred to in the text where appropriate.

PART I
CLAYS AND THEIR INDUSTRIAL USES

THE CLAY MINERALS
Classification
The clay minerals comprise a number of species of very diverse properties. The most useful classification of clay minerals for the purpose of this review is based on their crystal structure. This aspect has been exhaustively...
reviewed by Bailey, and thus only a summary of the more pertinent aspects needs to be presented here.

The clay minerals are hydrous layer-silicates and are part of the larger family of phyllosilicates. They consist essentially of continuous two-dimensional tetrahedral sheets of general composition T₂O₅ (with T a tetrahedrally coordinated cation, normally Si⁴⁺, Al³⁺, or Fe³⁺), which are combined, through the sharing of common anions, with immediately adjacent octahedral sheets (formed normally by the cations Mg²⁺, Al³⁺, Fe²⁺, and Fe³⁺ in octahedral coordination with oxygen or hydroxyl groups). The assemblages formed may consist of one tetrahedral sheet linked with one octahedral sheet, resulting in a 1:1 layer, or two tetrahedral sheets linked with one octahedral sheet, giving a 2:1 layer.

These fundamental layers may or may not be electrostatically neutral—if not, the excess layer charge is neutralized by various interlayer units, which include cations, cation groups, or integral sheets. In the trioctahedral minerals, all the cation positions in the octahedral sheet are filled while, in the dioctahedral minerals, only two-thirds of the cation positions are filled.

A convenient classification of the layer silicates into eight groups is based on the layer type (i.e. 1:1 or 2:1), the layer charge and the type of interlayer unit. Further subdivisions can be made on the basis of the type of octahedral sheet, the chemical composition and the geometry of the stacking sequence of the layers. Such a classification system is given in Table I.

Characteristics of the Clay Minerals

Most physical properties of clay minerals can be related either to the very small size of the individual particles or to the significant surface charge associated with these particles. The effect of heat on clay minerals and their behaviour when in suspension with water are two other characteristics that are technologically very important.

Particle Size and Shape

The ultimate crystals of the minerals in clays are extremely small. These crystallites are generally aggregated and agglomerated, sometimes as mono-mineralic units. The degree of cohesion in the aggregates varies considerably, and some units are broken down easily by gentle agitation while others are extremely difficult to separate into their individual crystallites.

Certain properties of powder compacts, such as texture, bulk density and porosity, depend largely on the character of the aggregates making up the powder, while the size of the crystallites is the important parameter determining the colloidal behaviour of suspensions.

The grain-size distribution of a powder can be evaluated by a range of methods, based on geometrical symmetry, hydrodynamic symmetry, or on measurements of surface area. However, the crystallites of clay minerals are far

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Group</th>
<th>Subgroup</th>
<th>Species</th>
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<tbody>
<tr>
<td>1:1</td>
<td>Kaolinite-serpentine</td>
<td>Kaolinite</td>
<td>Kaolinite, dickite, nacrite, halloysite</td>
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<td></td>
<td></td>
<td>Serpentine</td>
<td>Chrysotile, antigorite, lizardite, sepiolite, amesite, berthierine, brindleyite, baumite, greenalite, caryopilite, cronstedtite, pecoraite, kellyite</td>
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<td></td>
<td>Pyrophyllite-talc</td>
<td>Pyrophyllite</td>
<td>Pyrophyllite, terrophyllite, talc, willemite, minnesotaite, kerolite, pimelite</td>
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<tr>
<td></td>
<td></td>
<td>Talc</td>
<td>Montmorillonite, beidellite, nontronite, volchonskite</td>
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<td></td>
<td>Smectite</td>
<td>Dioctahedral smectite</td>
<td>Saponite, hectorite, saucnite, stevensite</td>
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<td></td>
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<td>Trioctahedral smectite</td>
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<td></td>
<td>Vermiculite</td>
<td>Dioctahedral vermiculite</td>
<td>Dioctahedral vermiculite</td>
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<td></td>
<td></td>
<td>Trioctahedral vermiculite</td>
<td>Trioctahedral vermiculite</td>
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<tr>
<td>2:1</td>
<td>Mica</td>
<td>Dioctahedral mica</td>
<td>Muscovite, paragonite, rosselite, chernyahovite, illite, phengite, slurge, mariposite, giauconite, ceaionite</td>
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<td></td>
<td></td>
<td>Trioctahedral mica</td>
<td>Phlogopite, biotite, anittte, siderophyllite, lepidolite, zinnwaldite, taeniolite, ephesite, hendricksite, muscovite</td>
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<td></td>
<td>Brittle mica</td>
<td>Dioctahedral brittle mica</td>
<td>Margarite</td>
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<td>Dioctahedral chlorite</td>
<td>Donbasite, Cookite, sudosite</td>
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<td></td>
<td>Trioctahedral chlorite</td>
<td>Clinochlore, chamotile, nimite, pennantite</td>
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<tr>
<td>2:1 Inverted ribbons</td>
<td>Palygorskite-sepiolite</td>
<td>Palygorskite</td>
<td>Palygorskite, yoforterite</td>
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<tr>
<td></td>
<td></td>
<td>Sepiolite</td>
<td>Sepiolite, toughlinite, talcoidite</td>
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from spherical. The ideal shape of the crystallites is a hexagonal plate, with a very large ratio of diameter to thickness, and thus the size of such particles cannot be described completely by a single parameter. This problem is partially solved by the use of the concept of "equivalent spherical diameter" or e.s.d., which refers the size of a particle to the radius of a sphere that will have the same behaviour in a fluid, for example the same settling velocity.

The sizes of the crystallites in various clay minerals differ considerably. The size range in kaolins is generally from 2 to 0.3 μm, while nearly all the particles of smectites are below 0.5 μm.

**Surface Charge on Particles**

Clay minerals in suspension have the ability to adsorb cations and anions, and to retain them in an exchangeable state. This ion-exchange capacity is the result of electrostatic charges on the surface of the particles, and it is generally expressed in terms of milli-equivalents (me) per 100 grams of material. Because both cations and anions are adsorbed at the same time, there must be both positive and negative charges on the surface of the particles. The cation-exchange capacities vary considerably, the values for kaolinite ranging from 3 to 15 me/100 g, for illite from 10 to 40 me/100 g, and for smectite from 80 to 150 me/100 g. There is less variation in the anion-exchange capacities, with values of 15 to 20 me/100 g for kaolinite and 20 to 30 me/100 g for smectite.

There are four mechanisms that could give rise to the surface charge on the surface of clay particles in suspension.

(a) Isomorphous lattice substitution of Al³⁺ for Si⁴⁺ in the tetrahedral sheet results in unsatisfied oxide linkages that will leave a net negative charge.

(b) The broken bonds at the edges of the layers give rise to two different types of charges. Above a pH value of about 2.5, the exposed hydroxyls of the broken silica tetrahedral sheet are ionized to form SiO⁻ units, resulting in a negative charge at that point on the broken edge, while the exposed aluminium octahedral groups can accept protons and thus will have a positive charge at low pH and a negative charge at high pH (above about 9).

(c) Positive or negative charges can be generated by the ionization of surface groups of the layers. The iso-electric point of silicate surfaces is at very low pH values, and thus SiO⁻ units will tend to predominate. As far as Al(OH)³⁻ units are concerned, it depends on the pH level whether a positive or negative charge is generated.

(d) The surface of the particles may be modified by the specific absorption of ions or polyions.

The nature and magnitude of the surface charges determine the behaviour of the particles when they are in a dilute suspension. A clay particle in suspension will attract cations to balance the negative surface charge. Some of these cations will be strongly adsorbed as a mono-molecular layer (termed the Stern layer), while the rest of the balancing cations will form a diffuse layer in which the concentration of cations drops off exponentially with distance from the particle surface. This system of a charged particle with a balancing cation layer can be regarded as a spherical condenser with an associated potential, termed the zeta potential.

The magnitude of the zeta potential is determined by the type of associated cation. Small and polyvalent cations are adsorbed strongly, mostly in the Stern layer, with the result that the zeta potential is small. Conversely, large monovalent cations result in a large zeta potential.

In reality, the charges on the surface of the particles are not evenly distributed. The edges of the crystallites can have both positive and negative sites as a result of the broken bonds, while the faces of the particles have only negative sites. Depending on the pH and the electrolyte present, these sites are neutralized to different extents.

If unsatisfied positive sites on the edges remain, the particles will tend to attract each other in an edge-to-face manner, resulting in a 'card house' structure. If the positive sites are largely satisfied, the particles will tend to pack in a face-to-face manner as a 'card pack' structure.

**Behaviour in Clay-Water Suspensions**

The behaviour of clay-water suspensions is very sensitive to strain rates. Only very dilute suspensions behave as Newtonian liquids, in which the rate of shear is directly proportional to the shear stress. Suspensions with higher concentrations of charged particles are usually shear-thinning or thixotropic. At even higher concentrations of solids, the system starts to show plastic behaviour with a yield stress that depends on the solids content.

**Rheology of Clay Suspensions.** Suspensions of clay materials with relatively high solids contents are used in the slip-casting process for the manufacture of ceramics. The flow properties and stability of such suspensions depend critically on the characteristics of the colloidal fraction, particularly on the zeta potential of the particles.

If the potential is low (of the order of 10 mV), the particles can approach each other closely enough for the short-range forces of attraction to operate, with the result that aggregates of particles, or flocs, form. In this flocculated state, dilute suspensions are unstable and will sediment out, forming a distinct layer of flocs and leaving a clear fluid. However, if the potential is high (of the order of 50 mV), the particles will repel one another so strongly that they cannot come close enough to aggregate. The suspension is now dispersed or deflocculated and it will not sediment out. Therefore, the replacement of alkali ions (Na⁺, K⁺, and Li⁺) with alkali earth ions (Ca²⁺, Mg²⁺) will change a stable suspension to one that will sediment out.

In general, the natural exchangeable cation in clay materials is predominantly calcium, with the result that the zeta potential will be low and the suspension will be flocculated. If the zeta potential is steadily increased by the pro-
gressive replacement of the calcium with a deflocculating cation (generally sodium), the degree of the flocculation will decrease, as shown in Fig. 1. The result of this change is that the viscosity of a suspension will decrease until the point is reached at which the attractive forces are neutralized. Further additions of sodium will result in over-dispersion, causing the viscosity to increase again as the system starts to coagulate. The particles unite to form larger aggregations that will not necessarily sediment out.

![Deflocculation curve of a typical kaolin](image)

**Fig. 1—Deflocculation curve of a typical kaolin**

A partially deflocculated suspension is usually thixotropic, meaning that, if it is left undisturbed, its viscosity will increase as a result of a build-up of structure within it. This thixotropic condition is readily destroyed by agitation.

Deflocculation thus makes it possible to form suspensions of high solids content and low viscosity. This is technologically important since less water needs to be removed during the drying of slip-cast articles. The ability of a clay material to be dispersed is evaluated by its critical concentration, defined as the solids concentration of a fully dispersed suspension having a viscosity of 5 P (poise).

**Plasticity of Clay Suspensions.** Plasticity can be defined rather formally as the property that allows a material to be deformed continuously and without rupture under an applied force that exceeds a certain minimum or yield value, and to retain the new shape when the applied force is removed. The definition describes the relationship between the applied stress and the resultant strain, and is thus purely qualitative, with no units of plasticity defined.

The underlying problem in a consideration of the plasticity of clay bodies is that this attribute is a composite, and not a fundamental, property. Because ceramists are much concerned with the shaping of a clay–water mass using different methods and materials, different aspects of this behaviour become important as cases vary. The plasticity of a clay material is thus frequently referred to in a general way as 'workability', while specific aspects are described by such imprecise terms as 'short' or 'fat' depending on the feel of the material, or 'strong' and 'lean' if the moulding behaviour is considered.

Plasticity is exhibited by clay materials within a comparatively narrow range of water additions. If not enough water is present, the mass cannot be moulded without rupture, while, if too much water has been added, the mass becomes a pourable slip. The range between these two extremes is sometimes termed the workability range. It varies with different clays; some materials will show a wide range and others a short range.

It is generally accepted that plasticity is associated with particles of colloidal size, i.e. particles so small that their behaviour is dominated by their surface character and not by their bulk properties. The larger the proportion of colloidal particles, the more plastic the material will be and the longer its workability range, but at the same time the amount of water needed to develop optimum plasticity is greater. The size distribution of all the particles also has an important influence on plasticity. Because of its better packing density, a material consisting only of colloidal particles is less plastic than a material composed of a range of particle sizes.

The type and amount of electrolyte (certain kinds of soluble salts and acids) that is present in the water also influence the plastic behaviour of a clay material considerably, because the balance between the attractive and repulsive forces between the clay particles depends on the type of exchangeable cations and anions absorbed on the surface of the particles.

Because of the complex and composite nature of plasticity, its precise definition by the measurement of a single attribute is not possible. It can thus be evaluated only by comparison of relevant behaviours: by subjective evaluation, by comparison of stress–strain relationships, or by correlation with physical and mechanical properties.

In practice, the proportion of water required to develop a body with a specific, well-recognized consistency is used as a measure of plasticity in a number of techniques, such as those devised by Atterberg and Pfefferkorn. The alternative approach involving the degree of deformation at stresses higher than the yield stress is used in the Linseis test, the BCRA compression plastometer, the Brabender plastograph, and cyclic torsion tests.

**Effect of Heat on Kaolin**

Because of the particular importance of clays to ceramics, the effect of heat on this material has been studied extensively, and there is a great deal of literature covering all aspects of its behaviour as a ceramic raw material. During firing, the kaolin takes part in a series of reactions that lead to the formation of a glass-rich phase. On cooling, this phase forms the vitreous bond in the ceramic
One of these reactions is the formation of the mineral mullite through a series of exothermic and endothermic transformations. To be of use as a refractory material, clay must have, first of all, a high fusion temperature. Because there is no definite melting point as such, but rather progressive fusion, the refractoriness of a clay material is evaluated in comparison with the behaviour of standardized materials. The most commonly used procedure is to compare the fusion of a conical test piece made from the clay material with that of cones made from a series of ceramic bodies of increasingly higher refactoriness. The fusion point used in this comparison is the point at which the cone has squatted to a specified degree. The refactoriness of the material then refers to the code of the standardized body; for example, Seger Cone 34 has an end-point of 1750°C.

**ORIGIN OF CLAYS**

Most clay minerals are formed by the transformation of primary silicates or volcanic glass as the result of hydrothermal or normal weathering processes. The very large amount of work done on the synthesis of clay minerals, which has been fully reviewed by Grim (see Bibliography), allows some general conclusions to be drawn regarding the environmental conditions favouring the formation of various clay minerals.

**Hydrothermal Alteration**

Although the alteration products of rocks subjected to hydrothermal action are not generally argillaceous, all the clay minerals have been found in hydrothermal bodies. The interrelationships between the different factors that influence the hypogene development of clay minerals are complex and frequently obscured by subsequent supergene events.

At low temperatures and pressures, the formation of kaolinite minerals is apparently enhanced by acidic conditions, while alkaline conditions favour the formation of either smectite or mica, depending on the concentration of magnesium or potassium. If the temperature is somewhat above 350°C and the pressure moderate, pyrophyllite forms instead of kaolinite, while boehmite forms if there is an excess of alumina. At more elevated temperatures and pressures, the relationships become complicated. For example, mica can form under acidic conditions, while kaolinite or pyrophyllite can form in the presence of excess potassium, depending on the particular conditions.

**Weathering**

The types and nature of the soils formed by normal weathering processes depend on a complex interaction between a number of factors, such as the parent rock (composition, texture, and structure), climatic conditions, time, topography, and the presence or absence of vegetation. It is thus possible that soils containing kaolin and soils containing smectite can both develop from the same parent rock, or that soils with the same clay-mineral composition can result from different parent rocks, depending on the weathering conditions.

Kaolinite is formed from acid igneous rocks if the weathering conditions are such that potash and magnesia are rapidly removed after the breakdown of the parent minerals. Under conditions of poor drainage and low rainfall, which allow the potash and magnesia to remain in the weathering environment, smectite and illite are formed. Similarly, kaolinite is formed from basic igneous rocks if the magnesia is removed as soon as it is released. If the leaching rate is less rapid, smectite may be formed first and kaolinite at a later stage. The renewed weathering of sediments follows the same pattern as for acid igneous rocks. It seems that the other alkalis and alkaline earths play a relatively minor role in determining the type of clay mineral formed, although it appears that the presence of calcium inhibits the development of kaolinite while enhancing the formation of smectite.

Halloysite has only rarely been found in weathering products, and special conditions are required for its formation. It is thought that the hydrous form of this mineral can result from the weathering of plagioclase if the conditions are neutral or slightly acidic.

**CLAY MATERIALS**

Clay materials can be classified on the basis of their composition, properties, origin, locality, or many other parameters. A useful classification when concerned with the use of the clay is whether the deposit was formed in situ, or whether it consists of material transported away from the place of formation. Residual or primary deposits are generally not contaminated with other material, while sedimentary or secondary deposits are generally classified as far as grain size is concerned.

A certain nomenclature has been developed over the years, such as kaolin, ball clay, bentonite, and fuller earths to describe groups of clay materials of economic importance. Such descriptive terms are not always used consistently, and some confusion exists as to the meaning of the terms.

**Kaolin**

Kaolin, also sometimes called China clay, is a white, fine-grained, naturally occurring earthy material. The name *kaolin* is derived from the Chinese 'Kao-ling' or Kauling', meaning 'high ridge'. This is the name of a range of hills near Yaochao Fu in the province of Kiangsi, where the material has been exploited for centuries.

The term *kaolinite* is used to denote the specific mineral species, as well as the mineral group comprising kaolinite, dickite, and nacrite. The term *kaolin* is less well-defined and is frequently used synonymously with 'kaolinitic clay material'. In the case of residual clays derived from coarse-grained feldspathic rocks, *kaolin* is used here only for the material that is extracted from the weathered rock and that consists essentially of kaolinite, while in the case of residual clays derived from fine-grained sediments, or transported clays of similar composition, the term is used for the materials as such, even though they may contain...
substantial amounts of minerals other than kaolinite.

**Ball Clay**

Historically, the term *ball clay* has been used to define the fine-grained, highly plastic kaolinitic sedimentary clays found specifically in the Dorset and Devonshire areas in the south of England. The better grades of this material fire white, and are sought after as the plastic component in ceramic whiteware bodies. The term *ball clay* does not describe any particular property of the clay material, nor does it have any geological significance, but it is believed that it is derived from the original method of extraction, which involved cutting out of the clay in open pits into 25 cm cubes. During handling between pit, rail wagon, or barge to factory, the cubes became rounded—hence the term *ball clay*. An alternative explanation is that the term is derived from the digging implement used formerly, which was known as a tubal.

Certain local clays are sometimes called ball clays mainly because of their highly plastic nature and the similarity between their superficial appearance and that of English ball clays.

**Bentonite**

Originally, the term *bentonite* was used to describe a highly plastic clay from Wyoming, but it was later broadened to include all clays that are produced by the alteration of volcanic ash *in situ* and that are largely composed of smectite. The rheological properties of bentonite depend largely on the structural characteristics and composition of the smectite, as well as on the type of exchangeable cation present. Consequently, there is a tendency in commercial usage to restrict the term *bentonite* to material with high colloidal and thixotropic properties, similar to the Wyoming material.

**Fullers Earths**

Since early times, oil and dirt particles have been removed from wool by a water slurry of absorbent earth, which ranged from fine-grained silts to clays. The process is called 'fulling'. At present, the term *fullers earths* is applied to any clay that has an adequate decolorizing and purifying capacity without having to be chemically activated. Fullers earths are not only used to clean wool, but also for decolorizing and purifying oils. Clays composed of palygorskite and certain kinds of smectite have superior adsorptive activity and are used extensively in this role.

**Industrial Use of Clays**

For some applications, the clay materials must comply with very stringent specifications while, for other uses, a variety of clay materials is acceptable. In any assessment of the usefulness of a clay material, it should be borne in mind that the requirements to be met by a clay are well-defined for some applications, but that there is no such information available for the majority of uses. Frequently, the reasons why a certain clay is used are not disclosed by the user, or the advantages that are allegedly gained through the use of a particular clay have no real scientific basis. For many applications, cost is a major, or even overriding, factor in the use of a particular clay.

The materials are always considered in their final beneficiated condition. Some kaolins require extensive beneficiation as, for example, the primary kaolins, while other materials are only mined selectively and marketed in the crude form, or are merely milled without any attempt to remove impurities.

**Clay Materials for Ceramics**

In the South African context, the ceramics industry is the major user of clay materials. Clays are used in the making of ceramic products because they facilitate the shaping of the body and the handling of the unfired articles. The clay fraction also plays a major part in the reactions taking place during vitrification, producing strength, permanency and other desirable properties in the article.

A large variety of clay materials are used as ceramic raw materials. Most of these materials are kaolins or kaolinitic-micaceous clays, and the major minerals present in these clay materials are kaolinite, illite, and quartz, with lesser or trace amounts of smectite, organic matter, feldspar, pyrophyllite, iron, and titanium-bearing minerals, etc. Other clay materials that are of interest in the production of ceramics are bentonite, attapulgite, pyrophyllite, and talc, but they are used to a much lesser extent.

A primary distinction within this group of clay materials is based on colour. As far as ceramics are concerned, the fired colour, and not the natural or unfired colour, is important. Two main groups of ceramic clays can thus be distinguished: dark-firing materials that are generally used only in the manufacture of structural clay products, and those materials that generally fire to a light colour and are used in whitewares. Another primary distinction is based on the plasticity or workability of the materials, which are defined broadly as plastic clays, semi-plastic clays, or clays of low plasticity.

**Whitewares**

Practically all whitewares are produced from fabricated bodies. Each kind of whiteware dictates certain specific properties that must be met by the clay materials if they are to be acceptable as raw materials for a particular application. For example, porcelain bodies must fire to a very white colour, stoneware bodies must have good plasticity and firing behaviour, and sanitary-ware bodies must have excellent casting properties.

Beneficiated primary kaolin is sought after because of its purity, but many residual kaolinitic clays also fire to acceptable whiteness. As such clay materials are generally not plastic, high-quality plastic clays that fire to a light colour are incorporated in fabricated whiteware bodies.

**Structural Clay Products**

The properties of the clay materials used in the making of structural clay products (face bricks, common bricks, hollow bricks and tiles, sewer pipes, floor tiles, roofing tiles, etc.) are poorly defined. Their fired colour ranges from yellow or dark ivory to deep red, and they have a rea-
sonably long firing range. They are generally not very plastic; otherwise, problems are encountered during the drying stage, particularly with products such as hollow blocks and roofing tiles. Some clays have natural bloating properties, and they are used for the production of lightweight aggregates.

A large variety of kaolinitic clay materials is used for the making of structural clay products. Frequently only a single naturally occurring material is used; sometimes two or more materials are blended to give the required properties, and only occasionally are other materials, such as fluxes and fillers, added to adjust the properties of a clay material or blend of clay materials.

Refractories

Certain naturally occurring kaolinitic clays have low flux contents (such as iron oxides, alkalis, and earth alkalis), and thus have the ability to be fired to high temperatures (in excess of Seger cone 27 or 1605°C) without melting or deforming. Both plastic ‘fire clay’ and non-plastic ‘flint clay’ types of refractory clay are found naturally. Beneficiated primary kaolins are sometimes pressed into briquettes and sintered to a high density for use as a greg or chamotte in refractories.

Refractory clays are used for the manufacture of a great variety of refractories for the metallurgical industry, in power generation, and for the construction of kilns and furnaces.

Fillers, Extenders, and Carriers

Clay materials have long been used as inert fillers or extenders, the only aim being to reduce the cost of the products. However, improved methods of refining the clays, as well as a better understanding of their properties, have made them valuable, and even essential, components of many materials.

Paper

The paper industry is a major consumer of kaolin, which is used both as a filler and as an ingredient of the surface coating. The kaolins must pass a series of very stringent tests, such as for abrasiveness, brightness, rheological behaviour, and particle-size distribution.

Filler kaolins must have a high brightness (reflectance values ranging from 80 to 84 per cent are acceptable) and a low ‘grit’ content (the residue on a 325-mesh screen should be less than 0.15 per cent). The presence of grit (usually fine quartz) is also evaluated by the Valley Abrasion Test, and the abrasion value should not exceed 13 to 16 mg. The particle-size distribution is not critical, but the bulk of the particles should be between 1 and 10 µm. The clay must disperse easily.

Coating kaolins are generally chemically bleached to achieve very high brightness, and values in the range 85 to 88 per cent are usually required for these materials. The clays are fractionated to have practically no particles larger than 2 µm, and the bulk of the material should be smaller than 1 µm. A most important property is the rheological behaviour of the kaolin in suspension. Suspensions with a solids content higher than 71 per cent, but with sufficient fluidity to pass freely through fine screens or to spread evenly at high coating-machine speeds, are generally required. Other important properties are abrasiveness (which must be low), degree of oil adsorption, and opacity (covering power).

Paint

Kaolin, bentonite, and attapulgite are widely used in paint formulations. The kaolins usually consist mainly of kaolinite and are water-washed, chemically bleached, and fractionated to particular particle-size ranges (generally 0.5 to 5 µm). Sometimes the kaolins are surface-modified by cladding of the particles with a variety of organic materials to make them hydrophobic, or they are calcined and then finely ground.

The surface characteristics of paint (eg. sheen) can be controlled by the addition of a clay material, which permits high pigment loading and adds to the hiding power of the paint. The amount of clay in the paint formula varies with the type of paint, and ranges from as low as 2 to 5 per cent in some enamels to more than 50 per cent in some interior-grade paints.

The specifications for paint-grade clays are diverse, but properties such as oil absorption, particle-size distribution, colour, and grit content (abrasiveness) are important.

Rubber

Both kaolin and bentonite are used in compounding rubber. The ‘hard’ kaolins produce rubbers, which have a high modulus of rupture and tensile strength, and good resistance to abrasion, and stiff uncured compounds, while the ‘soft’ kaolins produce weaker rubbers, with lower resistance to abrasion, and soft uncured compounds.

In ‘hard’ kaolin, 90 per cent of the particles are less than 2 µm, while the ‘soft’ kaolins are coarser, with only about 60 per cent of their particles finer than 2 µm. The grit content of the materials must be low (in high-grade kaolins it is less than 0.3 per cent), but brightness is not very important.

Polymers

Kaolin is used extensively in polymers because it is easily dispersed in the resin and does not separate out. The low relative density and light colour of kaolin are also advantages. Various types of kaolin are used, including organic-clad materials.

Printing Inks

The kaolins used in printing inks must have good brightness, be free from grit, and must be very fine (with substantially all the particles smaller than 2 µm). Organic-clad kaolins are used extensively.

Clays for Foundry-moulding Sands

The moulds used for the shaping of metal by the casting process are composed essentially of sand and clay. Naturally occurring sands were used originally, but synthetic or fabricated sands are now preferred since they can be prepared to meet exacting specifications with a high
degree of control of their properties. The granular particles are generally quartz sand, but calcined clay (chamotte) or zircon sand is used for special applications. A large proportion of used moulding sand is reclaimed and reconstituted by the addition of fresh clay to replace the clay material destroyed by the high operating temperatures.

The function of the clay fraction is to bind the sand particles together, and the properties of moulding sand influenced by the type and amount of clay used are the green and dry compressive strength, hot strength, and flowability.

The most commonly used clay material for moulding sands is bentonite. The exchangeable cation carried by the montmorillonite in the bentonite determines to a considerable degree the binding properties of the clay material. The principal clay for moulding sands in the United States of America, produced from the Wyoming region, carries sodium as the exchangeable cation, and it is common practice to chemically treat calcium- and magnesium-carrying bentonites with soda ash to change their properties in the direction of those possessed by Wyoming bentonite. However, for certain casting conditions, the properties of non-sodium montmorillonite are equal, or even superior, to those of sodium montmorillonite.

Highly plastic kaolinitic clays, such as fireclays and ball clays, are also widely used as binders for moulding sands. These clays generally have lower bonding power than bentonites, but they possess certain other desirable properties and are frequently mixed with bentonite in this application. Certain very fine-grained illite clays have a bonding power approaching that of montmorillonite and are also mixed with bentonite.

**Clays for Drilling Muds**

During rotary drilling, such as in the search and recovery of petroleum, a fluid is maintained in the hole at all times. The fluid is pumped continuously to the bottom of the hole through the hollow drill stem and, as it rises to the surface in the annular space between the stem and the wall of the hole, it removes the cuttings of the drilling process.

The rheological properties of drilling muds are of prime importance. The viscosity of the fluid must be higher than that of water to ensure the efficient removal of cuttings, but the fluid must still be pumpable and the optimum viscosity for general drilling conditions is about 15 cP (centipoise). The fluid should also be strongly thixotropic to prevent the settling of cuttings in the hole during temporary interruptions in pumping. It is very important that the rheological behaviour of the drilling mud should be altered relatively little by large variations in the concentrations of electrolytes caused, for example, when the hole suddenly encounters masses of salt or gypsum. Another function of drilling fluid is to confine formation fluids from ingress into the hole. As these formation fluids are generally under considerable pressure, drilling muds of high density are prepared by the addition of weighting materials such as finely ground barytes. The penetration of water from the drilling mud into the formations must also be restricted through the building up of an impervious coating on the wall of the hole.

Drilling fluids usually have the following composition (by volume): 65 to 98 per cent water, 2 to 30 per cent clay, and 0 to 35 per cent weighting material. The clay used most extensively under severe drilling conditions is sodium-carrying bentonite from Wyoming. This material yields large volumes of mud per ton, develops very high thixotropy, and builds up a thin but highly impervious layer on the wall of the hole. If highly saline conditions are encountered, clays composed of palygorskite are used, since the rheological properties of these muds vary little with large changes in electrolyte content.

**Miscellaneous Uses**

Certain bentonites, halloysites, and kaolins are used in the manufacture of catalysts for petroleum cracking and other organic reactions. Clay materials are also used as fillers and carriers in a multitude of products, such as asphalt and linoleum, medicines, pharmaceuticals and cosmetics, adhesives, pesticides, and soaps, or in the preparation of goods such as leather and fabrics. Specifications are seldom available and a large variety of clays seem to be satisfactory. Low cost appears to be an overriding consideration in many applications.

For more information on the less frequent, and sometimes unusual, uses of clays, the reader is referred to the extensive review by Grim that is listed in the Bibliography.

**MINING AND BENEFICIATION**

The choice of the mining and beneficiation techniques to be used at a particular clay deposit depends on a wide range of economic and technical factors. The economic factors are usually obvious, and include items such as the distance from the market or the cost of capital equipment, power, and labour, but their relative importance is far from constant, and they are critically influenced by many external factors. Some of the more important technical factors that need to be considered include the nature and size of the deposit, the quantity and quality of product required, and environmental aspects. The interrelationships of these factors are unique for each deposit.

**Mining Methods**

Because of the relatively low unit price of mined clay materials, their winning is restricted to low-cost operations. Short-range variation in the properties and quality of the clay materials, as well as localized contamination, affect the mining costs adversely. Other important factors that need to be taken into account are the subsequent methods of beneficiation, production level, size and locality of orebody, infrastructure, and ecological aspects.

A large variety of 'dry' mining methods for the loosening, loading, and hauling of clay materials are available, and the choice of mining system will depend on many factors. These methods offer the ability to mine selectively. In 'wet' mining, the faces of the clay pit are washed down with high-pressure water jets or 'monitors'. The pit wash
is collected in a sump at the bottom of the pit and, from there, it is pumped to a treatment plant. This method does not allow short-range selective mining.

**Beneficiation**

Because sedimentary clays are seldom beneficiated to any significant extent, this section deals exclusively with the beneficiation of residual kaolins, particularly for use in the ceramic and paper industries. In this context, *beneficiation* means the separation of the kaolin from the quartz, micaceous minerals, and other unwanted materials that make up the rest of the crude ore.

The method and degree of beneficiation are determined by the properties of the crude clay material and the requirements of the user, such as the degree of consolidation of the crude material, the particle-size distributions in the different phases, the character of the contaminant phases, and the required brightness, grit content, plasticity, particle-size distribution, etc.

Ore-dressing techniques are based on differences in one or more of the properties of the gangue and the mineral to be beneficiated; for example, differences in particle size, shape, density, magnetic susceptibility, colour, or surface chemistry. Unfortunately, the properties of the major minerals in the crude ore of kaolin are very similar. For instance, the densities of kaolinite, mica, quartz, and feldspar are all very close to 2.6 g/cm² and density separation is not practical. The magnetic susceptibility, colour, and surface chemistry of these major components of the crude material are also very similar, and beneficiation is generally feasible only if there is a significant difference in the particle size and shape of the various minerals present in the crude kaolin.

The two basic routes that can be followed in the beneficiation of kaolin from the crude material are dry processing or air flotation, and wet processing or classification by sedimentation in a water suspension.

**Dry Processing**

This process involves the drying and pulverizing of the raw material and the removal of the fine material by air currents. For example, the crude material is passed through a primary crusher and fed continuously into a rotary dryer, where the moisture is reduced from typically between 20 and 25 per cent to between 1 and 2 per cent. The dried material then passes through a pulverizer or attritor, from which particles of the required fineness are lifted by air currents. A series of separators and cyclones is used to achieve a good separation of particle sizes.

The dry process is relatively simple, but it is not used in the preparation of high-grade materials, especially when very low grit levels are required. The reason is that the crushing and dry attrition processes result in some breakdown of the large quartz grains into micrometre and sub-micrometre particles, which are then captured and retained in the clay fractions.

**Wet Processing**

This method is a much more complex procedure, while the capital requirement and energy consumption are also higher than those for a dry process. However, materials that will meet specifications with small tolerance limits can be produced more easily by a wet process. A modern wet beneficiation process comprises the steps of disintegration, refining or fractionation, and dewatering.

Most raw kaolins will disintegrate or disperse in water with only gentle agitation. Communion is thus unnecessary, and indeed undesirable, since it would increase the level of very fine quartz by crushing the coarse grains of quartz.

The finest screen or sieve that can be used in practice, a 400-mesh sieve, has openings of about 37 μm. However, such a screen is not fine enough to remove all the mica and quartz, and kaolin produced by screening will thus still contain an appreciable amount of these materials. Furthermore, with such very fine materials, other methods of separation, such as sedimentation in refining tanks, hydrocycloning and centrifuging are usually more economical.

The dewatering of the slurry, containing in general more than 70 per cent water, usually takes place in two stages: thickening, followed by drying. Raked tanks or centrifuges are mostly used for the initial thickening of the slurries. The thickened slurries are dewatered either by spray-drying or filtration, followed by final drying in rotary kilns, band dryers, or tray dryers. For effective filtration of the fine-particle slurry, pressure drops across the septum of considerably more than one atmosphere are needed. Vacuum filters are thus not used for dewatering kaolin slurries, but rather discontinuous filter presses capable of working at high pressures (up to 1 MPa).

Spray-dried material has a low bulk density, and it poses problems in shipping. Filter-pressed material, extruded as 'noodles' and dried, is preferred for bulk transportation. Material to be bagged is usually in the form of dried and pulverized filter cakes.

**Upgrading of Beneficiated Materials**

Efforts to upgrade the quality of clay materials are almost exclusively restricted to beneficiated kaolins, and such efforts are mainly concerned with improving either the whiteness or the rheological properties. Chemical or mechanical treatments, magnetic separation, flotation, or differential sedimentation can be used to improve the brightness of the kaolin, while fractionation, disintegration and surface treatments may be effective in improving its rheological properties.

**Chemical Treatment**

Hydrosulphites of sodium, zinc, and calcium (also called dithionites, the salts of the organic radical \( \{S_2O_3\}\)) added in amounts of up to 0.5 per cent by mass to the raw clay in the presence of sulphuric acid are often very effective in improving the brightness of natural kaolins. Ferric salts are converted to the ferrous form by this treatment, resulting in a reduction of the brown colour. This treatment affects only the free oxides of iron, and has little
influence on pyrites and iron-bearing aluminosilicates.

The brightness of some kaolins is adversely affected by the presence of small amounts of carbonaceous matter, which imparts a grey colour. The carbon can be removed, without destruction of the kaolinite, by an ozone treatment.

In fired products, lime is by far the most effective agent and, when it is added in the form of a very fine powder, clays containing up to 0.5 per cent iron oxide can be fired to a whiteness acceptable for most purposes.

Magnetic Separation

Specific contaminants can be removed by sophisticated selective or 'piggy-back' flotation procedures, but similar benefits can be obtained by high-intensity magnetic separation operated at field strengths of over 20 kG. This technique is effective in removing very fine magnetic and para-magnetic particles, such as hematite, pyrite, biotite micas, and iron-stained quartz or anatase, from the kaolin slurry, improving the brightness of the kaolinite correspondingly. The capital cost and total operating costs are high, making this method suitable only for the production of high-quality products. Nevertheless, it has become one of the main methods used to improve the brightness of paper-grade kaolins.

Mechanical Treatment

Kaolins frequently consist of aggregates of small particles of kaolinite strongly bound together. If the surfaces of these aggregates are iron-stained, the brightness of the material can be improved if the aggregates are torn apart or delaminated so that uncontaminated surfaces can be exposed. Delamination of the aggregates may also result in an improvement of the rheological properties of the kaolin.

Normal dispersion actions will not break down the aggregates, but delamination can be achieved with some kaolins by high-energy pugging and extrusion of a plastic mass with a water content of as low as 18 to 20 per cent. In such a very stiff condition, the particles of kaolinite cannot slide easily past one another and the high shear stresses tear the aggregates apart. The aggregates of some kaolins can also be delaminated by wet grinding with special very coarse sand or glass beads. The mills are rubber-lined to avoid comminution of the sand or glass beads.

The rheological properties of a kaolin can also be improved in certain instances if the kaolinite particles can be broken by very high-energy mechanical treatment. The effectiveness of such disintegration to lower the viscosity of the kaolin suspension would depend on the initial size and shape of the particles, and whether they can be broken down in such a way that they can move past one another more easily in a suspension.

Fractionation

The rheological properties of kaolin are adversely affected by the presence of smectites in amounts as small as 1 or 2 per cent. The smectites are naturally extremely fine-grained and can be eliminated by elutriation, using equipment such as decanter centrifuges to remove the very fine fraction from a kaolin suspension.

PART II

OCCURRENCE AND RESOURCES OF CLAY MATERIALS

The Republic of South Africa is well endowed with a wide range of clay materials. The occurrence and resources of the more important clay materials are summarized under the categories of residual kaolin derived from granites and from sediments, plastic clay, brickmaking clay, refractory clay, bentonite, and palygorskite.

GRANITE-DERIVED RESIDUAL KAOLIN

Residual kaolin derived from granitic rocks occurs in a large number of localities in the south-western and southern regions of the Cape Province, as well as in Namaqualand. Smaller and isolated deposits are also found in Natal and the Transvaal.

Cape Kaolin

The generic term Cape kaolin is used for that group of kaolins formed by in situ weathering of the coarsely porphyritic granite of the Cape Granite Suite, possibly with some hydrothermal alteration. The kaolinite is generally fairly coarse and therefore rather non-plastic. Because the weathered material has not been transported and is thus not contaminated, the refined kaolin exhibits a high degree of brightness.

The residual material, or growan, consists mainly of a mixture of kaolinite, quartz, and mica. Small amounts of halloysite are sometimes observed, and the presence of a smectite–illite mixed-layer mineral has also been reported. The unbeneficiated weathered granite has a pronounced bimodal particle-size distribution, as can be seen from Fig. 2. The fraction above about 40 µm consists essentially of quartz and mica, while the fraction below that size is practically pure kaolin. Because of the sharpness of the bimodal distribution, most of the kaolinite in the weathered material can be removed by simple fractionation processes. If the processes are efficient in removing most of the particles above about 20 µm, the beneficiated kaolin will be virtually free of quartz and mica.

There can be no doubt regarding the primary nature of the kaolin deposits of the Western Cape. Proof of the in situ decomposition of the Cape Granite is clearly given by the retention of the granitic texture in the undisturbed weathered material. Furthermore, transition zones from fully weathered to partially weathered to unweathered rock have frequently been found in boreholes, where the partially weathered material is characterized by the presence of biotite and grains of unaltered white feldspar.

One of the factors thought to have contributed to the very deep surface weathering of the coarse porphyritic granite is the strain in the big feldspar crystals. This strain is the result of the micropoikilitic intergrowth of feldspar and quartz, and enhances the disintegration of the rock. Another factor is the presence of prominent faults and joints, which allow good circulation of ground water. A structural control seems likely in many of the occurrences.
The shape of the deposits is generally trough-and-funnel-shaped with steep sides, and they parallel the local fault pattern. The extensive leaching that is required for the formation of kaolin is usually associated with a hot, humid tropical climate. Such a climate existed during the early and middle Miocene period.

The presence of stanniferous mineralization in the Stellenbosch region, as well as the widespread occurrence of spherical nodules and thin veins of tourmaline, are taken as evidence of hydrothermal activity. However, cassiterite has not been found elsewhere, and tourmaline is also characteristic of the Cape Granite. The remarkable depth of weathering is taken as another argument in favour of at least some low-temperature hydrothermal activity.

The consensus of opinion is thus that the kaolin deposits have been formed mainly by surface weathering, but the question of whether hydrothermal activity exerted any influence has not yet been settled.

Properties of Cape Kaolin

The Cape kaolins are remarkable mainly for three reasons:
(a) the high yield of the deposits—commonly 50 per cent or more;
(b) the virtual absence of grit, mica, and other impurities in the minus 20 μm fraction, which makes beneficiation simple;
(c) the high degree of brightness of the beneficiated kaolin.

The beneficiated kaolin consists mainly of a rather poorly crystallized kaolinite, with small amounts of quartz and mica. The crystal habit of the kaolinite is poorly defined, and scanning electron microscopy has revealed the presence of numerous stacks or booklets of kaolinite plates.

Typical chemical analyses of Cape kaolins are given in Table II. As far as the major elements are concerned, the Cape kaolins are similar to the kaolins of England and Germany. The Fe₂O₃ contents of some of the Cape kaolins may be as low as 0.15 per cent, but their TiO₂ content is distinctly higher than that of the English kaolins. The chemical analyses of the American and Brazilian kaolins, on the other hand, show low K₂O contents, reflecting the virtual absence of mica, but the TiO₂ contents are high.

In general, at least 80 per cent of the beneficiated kaolin consists of particles smaller than 10 μm, and 50 per cent smaller than 2 μm. In Fig. 3, the range in particle-size distribution of the Cape kaolins is compared with the distrib-

![Typical bimodal particle-size distribution of weathered Cape Granite](image)

Fig. 2—Typical bimodal particle-size distribution of weathered Cape Granite

![Comparison between the particle-size distribution of Cape kaolin and those of typical English kaolins](image)

Fig. 3—Comparison between the particle-size distribution of Cape kaolin and those of typical English kaolins
distribution of typical English ceramic-grade, coating-grade, and filler-grade kaolins. The Cape kaolins seem to be slightly finer than those English clays normally used for ceramics, but similar to the filler grades. Materials of the correct particle-size distribution for a coating-grade kaolin can obviously be prepared by a suitable fractionation process.

It is possible to beneficiate kaolins with very high brightness values without resorting to bleaching or a sophisticated mineral-separation technique. Brightness values ranging from 85 to 94 are general for raw kaolin, while the fired material has values of 93 to 95. The brightness values of the English filler grades for the paper industry range from 80 to 83.

Regarding ceramic applications, kaolin is non-plastic, deflocculates well and has good casting properties. Its dry strength is understandably low, while the PCE is between Seger cones 35 and 36.

The critical concentration of beneficiated Cape kaolin, when dispersed with sodium acrylate, is unfortunately low (59 to 61 per cent) when compared with that of coating-grade materials (70 to 72 per cent). The low critical concentration of Cape kaolin is probably due to its particle shape and size distribution and to the presence of small amounts of smectitic material.

Beneficiated Cape kaolin is thus a high-grade ceramic raw material, and it is also suitable as a filler or extender pigment in the paper, paint, and polymer industries; as a carrier for pesticides; and as one of the components in the manufacture of medicines, cosmetics, and pharmaceuticals. Unfortunately, its poor rheological properties when beneficiated makes it less suitable as a component in paper-coating formulations.

**Occurrences of Cape Kaolin**

Through the years, a number of surveys have been made of various kaolin-bearing regions by private interests, while a concerted exploration programme was undertaken by the Geological Survey during the period 1975 to 1979. Most of the known occurrences can conveniently be grouped into four areas: the Cape Peninsula, Vredenburg-Saldanha, Brackenfell-Kuilsrivier, Stellenbosch-Somerset West. A number of small and economically unimportant occurrences are also scattered throughout the Western Cape wherever Cape Granite is found.

None of the known important kaolin deposits of the Cape Peninsula occurs outside the Fish Hoek-Noordhoek-Kommetjie valley. Although granite-derived kaolin is known to occur widely in the Cape Peninsula, and new localities continue to be exposed through road works and building operations, such deposits are usually sterilized by urban development. The exploitable deposits are at Fish Hoek (Brakkloof), Kommetjie (Imhoff’s Gift), and Noordhoek (Chaplin’s Estate, Good Hope, Dassenberg).

At present beneficiated kaolin is produced only from the Brakkloof deposit, but the exploitation of the Noordhoek deposits must be imminent, provided that an acceptable solution to the ecological restraints can be found. The amount of beneficiated kaolin that could be recovered from the Noordhoek occurrences is estimated to be of the order of 10 Mt.

Kaolin has been found in many places in the Vredenburg peninsula, but the results of extensive prospecting during 1979 were rather disappointing in that no large deposits were found. However, a promising, though rather small, deposit was subsequently uncovered on the farm Langekleip 47. The occurrence of kaolin in this area seems to be much more restricted and less well-developed than in the Cape Peninsula, even though there are strong similarities between the two areas, such as the presence of coarse-grained granite and fracture zones and, presumably, the same climatic conditions during the geological past. More
active erosion conditions in the Vredenburg-Saldanha area may account for the removal of much of the weathered material, but indications of hydrothermal alteration are also totally lacking in this area. The experience gained with the Langeklip occurrence indicates that there could well be a fair number of medium to small kaolin occurrences in this area capable of yielding good-quality kaolin. Based on present knowledge, however, it seems doubtful whether more than about 1 Mt of beneficiated kaolin of good quality could be produced from this area.

Five noteworthy occurrences were delineated in the Brakenfell-Kuilsrivier area during the 1978 exploration programme of the Geological Survey. They occur at Hazendal, Riverside, Chateau, Montford, and Teen-die-bult.

Although the size of these deposits appears to be rather small—it is estimated that, at most, 2 Mt of beneficiated kaolin of good quality could be produced from them—the advantages of this area are the well-developed infrastructure, the relatively low value of the ground, and the smaller impact of ecological restraints.

Of the various occurrences investigated by the Geological Survey in the vicinity of Stellenbosch and Somerset West, only those on the property of the Stellenbosch Airstrip are of interest. The Airstrip deposit, in particular, is large and could yield about 5 Mt of good-quality beneficiated kaolin.

Namaqualand

Kaolin deposits are present in a very large area in the north-western part of the Republic, covering parts of the Vredendal, Vanrhynsdorp, and south-western Namaqualand Districts, the main occurrences being centred approximately on Bitterfontein. Deposits of good-quality primary kaolin were formed in this region by surface weathering of gneissic and metamorphic rocks. The residual material has many similarities to that derived from the granites in the Western Cape and consists mainly of kaolinite and quartz, while halloysite has been reported from some occurrences. The beneficiated Bitterfontein kaolins are similar in most respects to beneficiated Cape kaolin.

It is convenient to divide the occurrences geographically into an eastern group (near Nuwerus), a western group (near Landplaas), and a northern group (in the vicinity of Garies). The more important deposits are as follows:

- in the Nuwerus area: Niewoudts Nauwte, Erd Vark Gat, De Toekomst, Kersbosvlei,
- in the Landplaas area: Moedgewin, Klikprael, Hendriksvlei, Katooringvlei,
- in the Garies area: Rondabel.

Kaolin is not produced from any of these deposits at present, although a number of deposits were exploited in the past on a very limited scale. It is estimated that the following amounts of good-quality kaolin of high brightness could be beneficiated from these deposits:


<table>
<thead>
<tr>
<th>Location</th>
<th>Amount (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuwerus</td>
<td>0.5 to 0.6</td>
</tr>
<tr>
<td>Landplaas</td>
<td>2.2 to 4.0</td>
</tr>
<tr>
<td>Garies</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The formation of the deposits around Nuwerus is ascribed to normal surface-weathering processes on feldspathic rocks poor in ferromagnesian minerals. The environmental conditions at the time the deposits were formed were such that the potash was leached rapidly, with the result that the feldspar was altered directly to kaolinite, and not through an intermediate stage of sericite. Chemical analyses of fresh rock, partially weathered rock, and fully weathered material show the removal of SiO₂ and K₂O and an increase in H₂O. There is no change in the iron oxide content, and the conclusion is thus that the white kaolin was formed from rocks low in iron minerals. 

Analyses for trace elements indicated that there was no increase in the elements that are associated with hydrothermal action. The absence of the minerals fluorite, topaz, and tourmaline also points to a non-hydrothermal genesis for these clay deposits.

Other Occurrences

Apart from the major deposits of granite-derived kaolin in the Western Cape and the Namaqualand regions, only a few other deposits of good-quality kaolin that could be of economic importance are known, but it is always possible that more occurrences may be found.

Natal

Kaolin derived from granite occurs at a number of localities in the Inanda-Ndwedwe area of Natal. Although the extent of the deposits is limited and none of them are being exploited at present, good-quality material is found near Coqweni, Nozandla, and Appelsbosch

The deposits are clearly residual and their formation is ascribed to the downward percolation of surface water, which leached the feldspar-rich granite of the Basement Complex. The kaolinization took place particularly in a zone between the upper and the lower levels of the fluctuating water table, immediately below the contact between the granite and the overlying sediments of the Natal Group, as well as along fault zones.

Cape Province

A very large deposit of good-quality kaolin occurs as narrow lenses in a pegmatitic granite on the farm Rondeheuwel, north of Mossel Bay. The kaolin is derived from the weathering of vertical dolerite dykes in the George granite. The kaolinization of the dolerite and adjacent granite extends to about 30 m below the remnants of a horizontal capping of silcrete, which covers a wide area in this district.

The kaolin is used in a milled form by the ceramics industry for the production of whiteware. Apart from selective mining and hand cobbing to remove iron-stained fracture and joint portions, it is not otherwise beneficiated.

Residual Kaolin Derived from Sediments

Residual kaolin deposits derived from sedimentary rocks are particularly well developed around Grahamstown in
the Eastern Cape. These white-firing clay materials are extensively used in the ceramics industry and as filler material where low abrasiveness is not a critical requirement. Other kaolin occurrences derived from sedimentary rocks are found in Natal in the Ndwedwe–Appelsbosch District, in the Southern Cape near Albertinia, and in the Transvaal at Zebedia. These occurrences have not been investigated nearly to the same extent as those in the Grahamstown region, and it is likely that there are many occurrences that are not recorded.

Ceramic Clays from Grahamstown14,15

The clays from the Grahamstown region are probably the best known and most widely used ceramic raw materials in South Africa today. This area has a long history in ceramic manufacture, and extensive brick production occurred as early as 1875. Prospecting over the years has been intensive but probably by no means exhaustive, and new deposits that could be economically viable may in all likelihood still be discovered.

The Grahamstown clays are characterized by their diverse character. The large variations (even within a single deposit) in mineralogical composition, particle-size distribution, plasticity, colour, and vitrification behaviour are the result of their origin.

There is no doubt that the Grahamstown clay deposits are residual, i.e. they were formed in situ by the weathering of Cape and Karoo sediments. The extensive and unusually deep weathering of the shales is ascribed to the extraordinarily complete peneplanation that existed in the Grahamstown area at some period during Miocene to Tertiary times. The drainage under those conditions was very ineffective, with the consequence that water soaked deeply down and leached out the soluble constituents of the sediments. During the dry seasons, the water was drawn to the surface by capillary action, where the dissolved iron precipitated as oxides along the joint and bedding surfaces. Likewise, the dissolved silica precipitated as quartz in fracture zones and as the extensive silcrete cappings now present over the leached areas. The deposits associated with a specific peneplane are all of the same age.

Although it is certain that extensive leaching played the major role in the genesis of the deposits, the presence of small amounts of the minerals alunite, natro-alunite, wardite, and potassium feldspar in all the deposits (irrespective of the nature and age of the parent rock or whether the occurrences are associated with the Grahamstown Peneplane or the Coastal Plain) is strong evidence that there must have been a certain amount of low-level hydrothermal action at some time during the genesis of these deposits.

The Grahamstown Clay Deposits

There are numerous occurrences of clay in the Grahamstown region, all associated with a peneplane—either the Coastal Plain or the Grahamstown Peneplane—and covering an area stretching over a distance of more than 35 km from east to west. Because most of the occurrences are of limited extent or their material is of poor quality, only a few have been prospected in any detail or are in actual production. At present, only two of these deposits are known to be associated with the Coastal Plain, the rest of the deposits all being associated with the Grahamstown Peneplane.

The deposits occur as relic conical hills or on the edges of the Peneplane, and are generally partly covered by a well-developed capping of silcrete or a thick overburden of rubble. The thickness and hardness of the silcrete capping are decisive factors in the economic exploitation of the deposits. The original structural features of the parent rock, such as folds, joints, and bedding planes, are clearly preserved, while vein quartz is frequently found in association with shear zones. In many deposits there is heavy staining by iron oxides along the parting planes, but the staining is not penetrative and much of the iron oxide can be removed by a process of hand cobbing.

Because the quality of the kaolin depends on the lithology of the parent rock, good-quality kaolin is found only with the right combination of peneplane formation and geology. The physiographic and stratigraphic relationships of the important deposits in the Grahamstown area are summarized in Table III.

<table>
<thead>
<tr>
<th>Type</th>
<th>Deposit</th>
<th>Geological setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Plain</td>
<td>Avenue Park</td>
<td>Witteberg Group</td>
</tr>
<tr>
<td></td>
<td>Melrose</td>
<td></td>
</tr>
<tr>
<td>Grahamstown</td>
<td>Strowan</td>
<td>Prince Albert Form</td>
</tr>
<tr>
<td>Peneplane</td>
<td>Blakes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coronation</td>
<td>Dwyka Formation</td>
</tr>
<tr>
<td></td>
<td>Palmer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elandskloof</td>
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</tr>
<tr>
<td></td>
<td>Mayfield</td>
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</tr>
<tr>
<td></td>
<td>Beaconsfield</td>
<td></td>
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<tr>
<td></td>
<td>Webber</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wallace</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Gletwyn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crous</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glenhoek</td>
<td></td>
</tr>
</tbody>
</table>

There are numerous other occurrences associated with the Grahamstown Peneplane. They are invariably found close to the 650 m contour and just below the Grahamstown Silcrete Formation. The presence of deeply weathered material below the silcrete layer, away from the present edges of the Grahamstown Peneplane, is well known, but the thick silcrete cover makes occurrences of this kind economically unattractive.

Properties of the Grahamstown Clays

Although the mineralogy of the clay materials shows
large variations—not only from deposit to deposit but also within the deposits—some very clear compositional differences are apparent between the clay materials derived from different parent rocks, as can be seen from Table IV.

These differences are of great importance to ceramists. For example, clays derived from Witteberg shales contain appreciable but varying amounts of pyrophyllite, as well as small amounts of feldspar, while clays derived from Dwyka tillite or Ecca shales are devoid of pyrophyllite and also have less micaceous minerals than the Witteberg clays. These differences in mineralogical composition are reflected in the differences in ceramic properties.

The greatest problem faced by the clay producers in the Grahamstown region is the large variation in the properties of the weathered material within and between most of the deposits. These variations are the result of the rapid short-range changes in the original lithology of the parent rock, but the contorted structural nature of the parent rock frequently makes meaningful selective mining unrealistic.

The quality of the clay material supplied is thus generally not consistent, and some of the properties can change considerably over a short time. The consumer should thus be well aware not only that there are real differences between the different Grahamstown clays, but also that material from a particular deposit can vary greatly with time.

**TABLE IV**

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Content, %, in clays derived from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Witteberg shale</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>20 to 70</td>
</tr>
<tr>
<td>Mica - 2M1</td>
<td>10 to 25</td>
</tr>
<tr>
<td>Quartz</td>
<td>30 to 60</td>
</tr>
<tr>
<td>Pyrophyllite</td>
<td>Up to 35</td>
</tr>
<tr>
<td>Feldspar</td>
<td>5</td>
</tr>
</tbody>
</table>

It would appear that the type of parent rock has a distinct influence on the particle-size distribution of the weathered material. For example, the clays derived from the Dwyka Formation have a narrower particle-size distribution than those derived from the Bokkeveld and Witteberg shales. There is, unfortunately, no marked antiparallelism in the particle-size distributions of the individual minerals, with the result that there is a considerable amount of quartz with a grain size smaller than 20 μm in all the clays. Refining processes based on particle-size differentiation would thus be ineffective in producing a material consisting essentially of kaolinite.

It must be stressed that in most cases there is a considerable variation within the occurrences, and only general comparisons can be made. The type of parent rock has, to some extent, an influence on the ceramic properties of the clay materials, and some broad trends can be recognized.

The plasticity of the clays derived from the Dwyka tillite and shale of the Prince Albert Formation can be described as fair, while the Witteberg clays generally have good plasticity. The dry strengths of the clays derived from the Witteberg shale tend to be significantly higher than those of the Ecca and Dwyka clays.

The clays derived from Dwyka tillite and Ecca shale have a good white colour in their natural state, and the brightness of these materials compares fairly favourably with that of the beneficiated kaolins from the Western Cape. They are, indeed, frequently used as fillers where a low abrasiveness is not required. The fired colour of all the Grahamstown clay materials is also very good, and the materials are acceptable in this respect as materials for the production of whitewares\(^{10,16}\).

The Grahamstown clay materials are, with only few exceptions, utilized for ceramics without any real beneficiation, apart from limited selective mining, rough hand sorting, and sometimes cobbing to remove excessive iron staining. In general, the materials are supplied and used in the crude form, and any beneficiation is really only incidental during the manufacturing process of the user, for example the screening out of coarse quartz during the wet preparation of a ceramic body.

Other Occurrences

Residual kaolin derived from sedimentary rocks is also found in various other parts of the Republic of South Africa. These occurrences have not been investigated nearly to the same extent as those in the Grahamstown region, and it is likely that there are many occurrences that are not recorded. Deposits that could be of economic importance are found in Natal, the Transvaal and the Cape Province.

**Natal**

Sediment-derived residual kaolin occurs along the Tongaat–Durban road at Kingscliff and Afgroon. The weathering of the shales of the Natal Group was accompanied by the leaching of calcium, magnesium, and phosphorus, as well as by the oxidation of iron, resulting in the alteration of feldspar and mica to kaolinite and illite. The lenses of kaolinized shale are small in extent, and the shale has long been used by the local population for decorating their homes and for medicinal purposes.

In the unfired state, the clay materials are yellowish to cream-coloured, and there is no significant improvement after beneficiation to minus 10 μm, nor after a chemical bleaching process. The materials have low plasticity and a relatively short firing range, with sharp densification between about 1150 and 1200°C. They fire to a yellowish-cream colour\(^{13}\).

The poor colour of both the unfired and fired materials make them unsuitable as fillers in the paper industry or as raw materials for ceramic whitewares. Even if colour were not important, the presence of quartz in the fine fractions would preclude their use in applications where low abrasiveness is required.

The clays could be used as one of the raw materials in the production of coloured ceramics. However, the ton-
nagy of material available is small and the total reserves must be increased considerably before these clays can be regarded as the raw material for a ceramics industry.

**Cape Province**

There are a number of occurrences of clay materials near Albertinia, in the Riversdale District, with apparently similar features to those of the Grahamstown region. The clays are derived from steeply dipping Bokkeveld shales and argillaceous sandstones, and the deposits are found near or just below silcrete and ferricrete capstones. These clays are used extensively as raw materials in the whiteware ceramics industry.

**Transvaal**

A large deposit of white kaolin occurs just north of Zebediela, probably derived from a tuff or lava band of the Black Reef Formation. The clay material consists mainly of kaolinite, with minor quantities of quartz and sericite, and its colour ranges from white and cream to ochre and red. The white material is generally found towards the top of the bank and is thought to be the result of strong leaching. The material is used in the ceramics industry.

**The Western Cape Plastic Clays**

There are two well-known occurrences of high quality plastic clays in the Western Cape: in the Kraaifontein region (on the farm Eersterus), and in the Brackenfell region (on the farm Groenland). Because of their general appearance and high plasticity, they are known locally as ball clays.

The country rock on which the clay deposits and associated sediments rest belongs to the Malmesbury Formation. This formation consists of argillaceous shales, phyllites, and arenaceous rocks, which are folded and have undergone regional metamorphism. The Malmesbury Formation is completely covered by surface formations in the vicinity of the clay deposits, and there are thus no outcrops of these rocks. A few kilometres west of Brackenfell, post-Malmesbury Cape Granite outcrops. These rocks also occur as a large batholithic mass to the south of the deposits, forming the Bottelary hills.

The occurrences are overlain by up to 6 m of Cape Flats sand of Tertiary to Quaternary age. The sand is unconsolidated, contains no carbonate minerals, and varies in colour from off-white to rusty-brown. The bottom 3 m of the sand is admixed with a grey clay. The clay measure is about 3 m thick and grades downwards into impure peat or lignite, which varies in thickness from 0.3 to 1 m. The clay measure can be divided into an Upper Suite and a Lower Suite. Recognizable plant remains are evident in the peat, which also contains much clay material either admixed with the plant remains or as individual thin layers. The clay measure is underlain by a thick layer of sand of variable clay content.

**Properties of the Plastic Clays**

The Western Cape plastic clays consist largely of kaolinite, with varying amounts of quartz and sometimes small amounts of smectite. Micaceous minerals are completely absent, and these clays thus differ noticeably from the English ball clays in this respect. As far as their particle-size distribution is concerned, a direct comparison with the English ball clays is not possible, but it seems that the clay fraction of the Cape clays is finer-grained than the English ball clays. The particle-size distribution of the Cape clays is distinctly bimodal, with a large clay fraction (where the particles are all extremely small) and a much coarser fraction (consisting mainly of quartz grains). The ratio of clay fraction to coarse fraction varies considerably throughout the deposits.

The plastic behaviour and dispersion properties of these materials are complex, but depend largely on the amount of clay fraction and organic matter present in them. These materials are important components of fabricated white-ware bodies.

**Origin of the Plastic Clays**

A major and still unsolved problem is the origin of the clay measures. The kaolinite of this clay is disordered, while that derived from the granites is fairly well ordered. On the other hand, the Malmesbury shales contain appreciable amounts of quartz and micaceous minerals, while the plastic clay is practically monomineralic. Furthermore, most of the plastic clays from the Western Cape, if not all, are associated with units of peat or lignite. The presence of macchia pollen and palm spores indicates contrasting climates of cool, wet winters and dry, windy summers to subtropical conditions. The clay unit is probably of late Cainozoic age.

One possibility is that the clay measures were deposited either in a lacustrine or fluvio-lacustrine environment. The presence of the organic matter would then indicate a sloping or hilly country from which plant matter was derived. Under such conditions, the sandy units and the peat units would indicate deposition in shallow water, whereas the very fine-grained pure-clay units point to deep-water conditions.

However, it is confusing to find thin clay units, only a few millimetres thick, within peat or lignite units. If the essentially monomineralic nature of the clay units is also taken into consideration, an alternative possibility should be considered: namely, that the clay units were formed by the in situ alteration of volcanic ash deposited periodically in shallow, highly acidic waters.

**Brickmaking Clays**

A large variety of clay materials is used locally for the making of structural clay products, but such clays invariably contain large proportions of kaolinite and quartz, while micaceous minerals are seldom absent. These clays generally contain appreciable amounts of iron compounds, with the result that they fire to a dark colour. It should be stressed that these materials are place-bound, and only in very exceptional circumstances would these materials be transported to other production centres.

**Western Cape**

Clays suitable for the manufacture of structural clay
products (face and common bricks, floor tiles, roofing tiles, sewer pipes, etc.) are found throughout the Western Cape. The fired colour of these materials ranges from yellow or dark ivory to deep red, and they are generally not very plastic. There is a fair variation in the properties of these clays, making it possible to produce a fairly wide range of products. A grouping found useful for these brickmaking clays takes into account the geological formation to which they belong, as well as their mineralogical composition and firing behaviour.

The geological relationships of the materials are usually easily established. In the majority of cases, it is quite clear whether the material is a Malmesbury shale (e.g. by its characteristically steeply dipping layered structure) or a more recent sediment (e.g. by its horizontal bedding, or because it overlies the Malmesbury sediments).

The firing range of these materials is a distinctive parameter. Firing range refers to the increase in temperature required to increase the degree of vitrification or densification by a certain amount. In the evaluation of these clays, the firing range is specified as the difference in the temperatures resulting in water absorptions of 15 and 10 per cent.

Based on the above criteria, the brickmaking clays of the Western Cape can be classified into three groups.

Group A

The clay materials allocated to this group are all Malmesbury shales and weathered phyllites, and they consist mainly of kaolinite, hydrous mica, and quartz, the kaolinite and hydrous mica being present in about equal amounts. They are generally red-burning, are not very plastic, and are characterized by their short firing range— as low as 25°C but not more than 70°C. Their occurrence is widespread: from Cape Town to Paarl, from Gordons Bay to Kalbaskraal and, in all likelihood, even further afield. They are really suitable only for the making of common bricks, but face bricks and heavy tiles can be produced with careful production control.

Group B

The materials in this group are also Malmesbury shales and weathered phyllites. These clays consist of kaolinite, hydrous mica, and quartz, with generally more kaolinite than hydrous mica. Their firing colours are similar to those of the Group A materials, but their firing ranges are longer than those of Group A, making it easier to produce a consistent product. Their plasticity is usually still too poor for these materials to be used for anything other than bricks and heavy tiles. The Group B materials have been found only in the central area—at Bellville, Brackenfell, Stellenbosch, Durbanville and Kalbaskraal—but they may have a wider distribution.

Group C

The materials belonging to this group are all recent sediments. They consist mainly of kaolinite and quartz, but very small amounts of hydrous mica are also present. They have long firing ranges (generally over 120°C), fire to a light buff to golden-brown colour, and are generally more plastic than Group A and Group B materials. Materials with these characteristics are known as yet only at Koelenhof, Dassenberg (near Kalbaskraal), and Phesanetekraal. They are very important for the production of sewer pipes and tiles, while the addition of these clays to Group A and B materials considerably facilitates the production of a better-class product such as face bricks.

Transvaal

The clay-based ceramics industry of the Transvaal is well served by a wide range of raw materials suitable for the manufacture of face and common bricks, roof tiles, and floor tiles. These materials range from hard shales of low plasticity to soft clays of very high plasticity, and they develop fired colours ranging from light beige and yellow to deep red. Two broad classes of brickmaking materials can be defined based on age: namely, those of Proterozoic age and those of the Vryheid Formation of the Ecca Group.

Proterozoic Clays

The Proterozoic lithologies that can be used for brickmaking belong to the Witwatersrand, Transvaal and Ventersdorp Supergroups. Despite the vast age span and extensive surface exposures, these weathered products of shales and igneous rocks account for only about 20 per cent of the clay-brick production of the Transvaal.

The Proterozoic materials exhibit remarkable similarities in their brickmaking properties, and only two types need be identified. The shales, composed mainly of anhydrous micas and quartz in their unweathered state, weather to illite and hydromicas. The hard, impervious nature of the indurated shales and poorly developed weathering profiles of the Transvaal Highveld ensure that degradation of the primary mineralogy is incomplete; thus, these shales are refractory and of low plasticity. The vitrification range is very long, and the water absorption does not fall below 15 per cent at practicable temperatures for brick kilns.

Lavas and minor intrusives of ultrabasic to andesitic composition constitute the second group of Proterozoic brickmaking materials. The anhydrous high-temperature primary minerals, mainly pyroxene and plagioclase, are unstable and break down readily to a clay-rich assemblage of calcic smectite and interlayered chlorite–illite. Kaolin
and quartz are minor accessories. The iron content is usually between 10 and 20 per cent Fe₂O₃, yielding very dark red to blue–black vitrified fired colours. In contrast to the shales, these clays have a very high plasticity, very short vitrification range, and a strong tendency to crack during drying, all of which would lead to very poor yields of good quality products even in the most sophisticated of brickworks. The two Proterozoic types of raw materials described above are complementary and can be blended to produce bricks of reasonable quality, although most such production is for the non-face market.

Karoo Clays

The sedimentary rocks of the Karoo Sequence used by the Transvaal brickmaking industry represent a part of the coal-measures facies of the Vryheid Formation.

The same lithological sequence is widely observed and can be generalized, from the base upwards, as follows,

(a) Low-grade coal or a very plastic black clay of high carbon content is present.

(b) A plastic non-refractory kaolinite of low quartz content occurs, and grades from black at the base to light purple–grey at the top with decreasing carbon content.

(c) A hard refractory flint clay occurs within the plastic kaolinite at many localities and, with increasing frequency, to the east and north of Pretoria until the flint clay is the predominant lithology.

(d) A white to pale yellow or brown kaolinite of moderate refractoriness and plasticity, and of higher quartz content than the plastic kaolin, is present. The quartz content tends to increase upwards, and a shaley texture is generally present. This unit tends to be predominant on the West Rand, and absent or poorly developed to the east of Johannesburg.

(e) A sandstone horizon frequently occurs as the next member of the sequence. This unit is generally medium- to coarse-grained but varies considerably in thickness, induration, and lateral persistence.

(f) Above the sandstone on the East Rand, there is a sandy, iron-stained kaolinite. This unit invariably has a significant content of smectite-group minerals, which impart a short firing range and low vitrification temperature.

The origin of the clay sequence described above is controversial, and models implying both diagenetic and primary origins for the clay mineralogy have been suggested.

Brickmaking Properties

It can be deduced from the descriptions given above that there is a correlation between plasticity and refractoriness, and that, in general, the highly plastic clays vitrify more rapidly and at lower temperatures than do the less plastic varieties. This applies to both the Proterozoic and the Karoo clays.

The highly plastic, smectitic clays of both Proterozoic and Ecca age have a firing range of approximately 50°C, and reach a water absorption of 10 per cent by 950°C. The Proterozoic shales of low plasticity have a firing range of about 300°C, and do not achieve a water absorption of 10 per cent below the practical temperature limit for brick-making kilns of 1200°C. The Ecca shales and clays of moderate plasticity have a good balance of forming, drying, and firing properties that render them ideal for brick-making purposes. Typical firing ranges for the kaolinitic Ecca shales are between 100 and 150°C, and a water absorption of 10 per cent is generally achieved at between 1025 and 1070°C.

Natal and Orange Free State

There is not much information available on the brick-making clays of this region. However, it appears that all the suitable clays are red-burning and thus no light-coloured bricks can be produced.

The friable carbonaceous shales of the Pietermaritzburg and Vryheid Formations of the Ecca Group are used extensively for brick manufacture in the tugela Basin region. These shales, which are often intruded by minor dolerite, are generally overlain by Quaternary Berea Red Sand sediments. The hard material weathers rapidly on exposure, and sufficient plasticity develops within a few days.

The siltstones and shales of the Volksrust Formation of the Ecca Group are exploited in the Odendaalsrus area, while Beaufort shales are used near Bloemfontein. In the Kimberley area, the Prince Albert shales of the Ecca Group are mined for brickmaking.

REFRACTORY CLAYS

A classification generally used in South Africa is based on two important quality-determining parameters: bulk density (Table V), and alumina content on a calcined basis (Table VI). Bulk density is inversely related to porosity and to some extent reflects the plasticity of the clay, as well as the resistance of the fired product to slag attack, while the alumina content gives an indication of the refractoriness of the material.

<table>
<thead>
<tr>
<th>Type of clay</th>
<th>Bulk density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flint clay</td>
<td>Higher than 2,32</td>
</tr>
<tr>
<td>Semi-flint fire-clay</td>
<td>2,00 to 2,32</td>
</tr>
<tr>
<td>Semi-plastic fire-clay</td>
<td>1,90 to 2,00</td>
</tr>
<tr>
<td>Plastic fire-clay</td>
<td>Lower than 1,90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade of clay</th>
<th>Al₂O₃ content after calcining %</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Higher than 44,0</td>
</tr>
<tr>
<td>II</td>
<td>44 to 40</td>
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<tr>
<td>III</td>
<td>40 to 38</td>
</tr>
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<td>IV</td>
<td>Lower than 38</td>
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</tbody>
</table>

TABLE V

<table>
<thead>
<tr>
<th>BULK DENSITY OF REFRACTORY CLAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of clay</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Flint clay</td>
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<tr>
<td>Semi-flint fire-clay</td>
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TABLE VI

<table>
<thead>
<tr>
<th>ALUMINA CONTENT OF REFRACTORY CLAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade of clay</td>
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<tr>
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</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>II</td>
</tr>
<tr>
<td>III</td>
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<tr>
<td>IV</td>
</tr>
</tbody>
</table>
Occurrences of Refractory Clays

Refractory clays are known to occur only in the Transvaal, and a full inventory of all the deposits of such materials was compiled in 1987 by Bredell22, who noted whether their exploitation was active, abandoned, or dormant. The refractory clays in the Witwatersrand area range from plastic to semi-flint types, and are confined to the Vryheid Formation of the Karoo Sequence, which was deposited on the uneven floor of older rocks—mainly the Chuniespoort Group of the Transvaal Sequence. The total production of high-quality flint clay and a large proportion of the production of semi-flint clay come from the Pretoria–Belfast area. These deposits are generally located near the edges of the numerous outliers of Ecca sediments fringing the continuous sheet of Karoo rocks extending southwards.

The main productive deposits in the Witwatersrand region are at Boksburg, Brakpan, Springs, Modder East, Marievale, Olifantsfontein, Lawley and Vereeniging21,24,25. Several occurrences in both the East Rand and the West Rand were recently investigated in detail by Bredell22. The type and grade of the refractory clays found in this region vary considerably, and materials ranging from plastic to semi-flint clays are sometimes found in one deposit.

Flint and semi-flint types of refractory clay occur in the vicinity of Bon Accord, Hammanskraal Boekenhousts-kloofdrift, Nooitgedacht, Witbank, Middelburg, Bronkhorstspruit, Belfast and Soutpansberg21,23. The deposits of high-quality material tend to be thinner and smaller than the more plastic refractory clays of the Witwatersrand area.

The better-quality refractory clays are used for the manufacture of fireclay refractory bricks, while the clays of low refractoriness (the so-called chocolate-brown plastic clays) are used for the making of building bricks, tiles and pipes. Some of the clays fire to a good whiteness and are thus suitable for the production of whitewares10.

Flint clay is sold either in the raw state or as a calcined material (chamotte). It is used in the manufacture of high-quality super-duty fireclay bricks and is much in demand by the steel industry.

Resources of Refractory Clays

As pointed out by Bredell22, the lack of intensive exploration, even in producing areas, as well as the confidential nature of company data, renders the calculation of the resources of refractory clays highly conjectural. Comparisons between estimations by different investigators are also made difficult because of the inexact terminology used.

Witwatersrand Region

Bredell22 summarized his calculations of resources of refractory clays on the East Rand as follows:

(1) indicated resources of semi-flint and plastic clay with good refractoriness (PCE 34 to 35) within the boundaries of active mining areas: 10,5 Mt
(2) indicated resources of semi-flint, semi-plastic and plastic clay with good refractoriness (PCE 34 to 35) in areas where mining is potentially feasible: 11,3 Mt
(3) indicated resources of semi-flint, semi-plastic and plastic clay with low refractoriness (PCE 26 to 33) in areas where mining is potentially feasible: 22,4 Mt
(4) refractory clay sterilized by urban development (as at 1987): 26,6 Mt.

Bredell22 also conservatively estimated the inferred resources of all refractory clays on the West Rand to be in excess of 200 Mt, of which about 70 per cent would consist of clay with good refractoriness (PCE 34 to 35), 27 per cent of clay with low refractoriness (PCE 29 to 33), and 3 per cent of non-refractory clay.

Pretoria–Belfast Region

In 1965, Bennetts23 estimated the probable ore reserves of flint clay to be of the order of 1 to 2 Mt, but stated that underground mining could increase this figure to over 50 Mt. At the same time, however, the industry estimated the proven reserves of high-quality flint clay at about 3,5 Mt, with additional estimated reserves of about 4 Mt, as reported by Heckroodt21.

For his estimation of resources, Bredell22 grouped the refractory clays into three categories:

(i) Grade I flint clay: demonstrated resources of 15,2 Mt, of which only 3,4 Mt represent measured reserves under the prevailing conditions; inferred resources of 1,0 Mt;
(ii) Grade I semi-flint and Grade II and III flint clay: demonstrated resources of 4,6 Mt; inferred resources of 1,0 Mt;
(iii) Grade I to III plastic clay: demonstrated resources of 1,2 Mt; inferred resources of 0,5 Mt.

Genesis

Bredell22 suggested that the purity and type of the refractory clay deposited was determined by pH-controlled differential flocculation, rather than by the nature of the source material or post-depositional alteration. In acidic environments, as could have been caused by the concentration of organic acids in swamplike sediments during the early stages of Ecca deposition, almost pure kaolinite would have been deposited from a mixed clay-mineral suspension. In the smaller proximal basins and at low pH, kaolinite particles would have flocculated in an edge-to-face manner, giving rise to small deposits of flint clay. At higher pH, flocculation tends to be face-to-face and, therefore, deposits of plastic clay would have formed in the larger, more distal brackish basins. The gradual displacement of the acidic conditions by a fluvial and lacustrine environment would have reduced the efficiency of differential flocculation and eventually led to the deposition of shale.

By comparing the rubidium and strontium contents of the refractory clays from different regions with the concentration of these trace elements in kaolinite derived from in situ weathering of probable parent rocks, Bredell22 concluded that the West Rand clays received most of their kaolinite from Halfway House Granite, with a possible
contribution from Witwatersrand shale, while the clays from the East Rand were derived from both Halfway House Granite and granite from the Bushveld Complex. The granite from the Bushveld also served as the main source of kaolinite for both the flint and the plastic clays in the Pretoria–Belfast area, with possible contributions from Rooiberg felsite, shales of the Pretoria Group, and Waterberg arkose.

**BENTONITE**

Clay materials similar to the Southern Bentonites of the USA are found in a number of localities in the Republic. The exchangeable cations are mainly calcium and magnesium, but the clay can readily be converted to a high-swelling sodium bentonite by treatment with sodium carbonate. The bentonite can also be effectively activated by strong acids such as hydrochloric or sulphuric acid to greatly increase its bleaching action.

**Occurrences of Bentonite**

Bentonites are known to occur in four localities in South Africa.

**Koppies District, OFS**

Major deposits of bentonite are found on the farms Ocean and Blaauwboschpoort, with smaller occurrences on other farms in the vicinity. The material occurs below an overburden of 12 m of Ecca shale, which occupies embayments in the Swaziland schists. The occurrences are flat-lying and lenticular, with a hard footwall and hanging-wall of shale, caused by local silicification, probably through the release of silica from the bentonite.

**Knysna District**

The deposit on Roode Farm (near Plettenberg Bay) is part of a succession of clays and sands of the Upper Wood Beds of the Enon Formation. The deposit is lenticular, dipping eastwards, with a thickness that varies from 0,15 to 2,5 m and an overburden that could be as thick as 61 m. The material is sometimes interstratified with sandstone.

**Wodehouse District**

A bentonite layer, between 1 and 2 m thick, occurs in the Red Beds on the farms Prongs Berg and Tiger Klip. The bentonite is underlain by yellowish sandstone and overlain by red mudstone, which has undergone extensive silicification. Thin lenses of sandstone are interbedded locally. It was estimated that up to 1 Mt of bentonitic material is available but, because of its variable quality, the occurrence may not be economically viable.

**Northern Natal**

A deposit of impure bentonite occurs in the Upper Lebombo Stage of the Stormberg Series, near Mkuze. The reserves are probably large. This deposit was probably formed by the alteration of perlite, perlitic pillow lava, and tuff.

**Properties of Bentonite**

The bentonites from the Koppies, Knysna and Wodehouse Districts are very similar and consist mainly of montmorillonite and some quartz. Cristobalite is generally present, sometimes only in trace amounts. The cation-exchange capacity of good-quality material ranges from 94 to 99 me per 100 g of dry clay, the exchangeable cations being essentially calcium and magnesium in equal proportions. The endothermic loss of crystalline water peaks at about 700°C.

The bentonite occurring in northern Natal consists of smectite, some kaolinite, and a high proportion of cristobalite. This material is similar to the Ultramarina bentonite from Mozambique and it may have ceramic applications since it fires white and imparts high dry strength to the body.

The presence of cristobalite and the absence of large amounts of quartz in the bentonites from the Koppies, Knysna and Wodehouse Districts point to the *in situ* alteration of layered volcanic tuff, rather than the alteration of Swaziland schists or Ecca shales, as the origin of these materials. Bedding laminations and the presence of thin lenses of sandstone in the deposits in the Wodehouse District are evidence that the ash was deposited in shallow water, while it is also known that at least eight volcanic vents of Stormberg age exist within 8 km of these occurrences.

**PALLYGORSKITE**

The resources of palygorskite in the Republic are large, but their exploitation is limited. Considerable tonnages of this material are imported into the country, even though some of the local palygorskite can be beneficiated to compete on quality with the foreign material.

Palygorskite is a product of neoformation during pedogenesis in arid to semi-arid regions, together with the formation of smectite or carbonates. At present, palygorskite is known to occur at Dwaalboom (Rustenburg District), Northam, Naboomspruit, CreCy, Immerpan, Lydenburg and Hotazel.

There are many similarities between the deposits. The palygorskite layer, between 1 and 4 m thick, usually occurs below an overburden of black turf or surface limestone. The top part of the layer is generally dissected by carbonate veins. The best-quality material is found in the middle part, which grades downwards into sandy or gravelly palygorskite.

It would seem that the parent material had no influence on the genesis of the palygorskite, since it is found above granite, basalt, norite and manganese ore. Palygorskite is never found in association with lacustrine sediments.

The extent of this resource is not known, but it is clear that it is large. The genetic association of palygorskite with surface limestones could assist in exploration and, because of the widespread distribution of calcrete in South Africa, it is probable that the distribution of palygorskite is far more extensive than is known at present.

**CONCLUSION**

As this review has shown, clays, though less glamorous than many other raw materials, are vital to technological...
societies. They are required for the manufacture of building materials, refractories, crockery, sanitary ware, paper, paint, pharmaceuticals and a host of other products. Certain clay materials are also important catalysts, or they are used as absorbents in many applications.

The Republic of South Africa is fortunate in the wide range of clays that it possesses, although many of the deposits are yet to be exploited. Further study and exploration may yet reveal additional sources.

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