

Title: Geometallurgy: driving innovation in the mining value chain

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Abstract

Geometallurgy is a discipline which seeks to improve the sustainability of the extraction of metals and minerals by promoting the smarter use of non-renewable resources, better energy efficiency and greater use of renewable energy. To achieve these goals, development of innovative technologies and approaches are being developed along the entire commodity value chain, starting with exploration and extraction and extending to re-use and recycling. This paper discusses the geometallurgy of industrial minerals with special emphasis on kaolin, a versatile industrial mineral applied in ceramics, paper, paint, plastics, rubber, pharmaceuticals, cosmetics, ink, sealants, adhesives, sanitaryware, glass fibre, toothpaste, animal feed, etc.. Aspects of kaolin extraction in southwest UK are analysed from a geometallurgical perspective. While geometallurgy already features in kaolin extraction, its role can be significantly expanded by combining advanced in-pit characterisation and orebody modelling with integrated planning and control of the refining and calcination process. This paper highlights the importance of innovation in realising the full potential of geometallurgy.

INTRODUCTION

The Brundtland Report (1987) defines sustainable development as “development which meets the needs of the present generation without compromising the ability of future generations to meet their needs”. Given that the Earth’s natural resources are strictly limited, this aims for more efficient cycling of materials, as envisaged by the circular economy concept and consideration of waste hierarchies. While practical limits apply to the cycling of materials, extraction of natural resources will continue to play a significant role for the foreseeable future. In line with the principle of sustainable development, extraction should be focussed on zero harm, zero waste, and zero emission practices while being effective, efficient, environmentally–friendly, and economic. Geometallurgy seeks to promote sustainable development of mineral resources by ensuring that all stages of extraction are performed in an optimal manner from a technical, environmental and social perspective. To harness the full potential of geometallurgy, innovative technologies and approaches are emerging. Although geometallurgy is commonly associated with metals, this paper explores opportunities for geometallurgy during the extraction of an industrial mineral.

INDUSTRIAL MINERALS

Industrial minerals are a class of geological materials which are mined for commercial value which does not depend primarily on recovery of metals or fuel. Industrial minerals, which are also synthetically produced, find application in a wide range of everyday products. Applications include (Shtiza et al., 2015):

- glass (almost 100% made from minerals such as silica, dolomite, calcium carbonate, borate, alumina etc.),
- paper (consisting up to 50% of calcium carbonate, talc, kaolin, bentonite, etc.),

- paint (containing 50% of calcium carbonate, calcined kaolin, quartz, cristobalite, talc, bentonite, mica, perlite, etc.),
- ceramics (can be up to 100% feldspar, clay and kaolin, lime, talc, silica, etc.)

A passenger car can contain up to 250 to 300 kg of minerals in the form of additives to:

- rubber (talc, calcined kaolin, calcium carbonate, etc.),
- plastics (talc, kaolin, calcium carbonate, silica, etc.),
- glass,
- casting (bentonite, silica, wollastonite, etc.) parts.

The building industry uses even larger tonnages of industrial minerals; a family house typically contains up to 150 tonnes of minerals in:

- bricks and tiles,
- cement (clay, silica, calcium carbonate, etc.),
- plaster and plasterboard (gypsum, hydrated lime, calcium carbonate, etc.),
- insulation (perlite),
- glass, paint, ceramics, etc.

Although bulk quantities of industrial minerals are applied in relatively low-value products, smaller amounts of industrial minerals can also be found in high-value products such as pharmaceuticals, adhesives, toothpaste, etc.. The scale of industrial mineral production is significant: in Europe alone, 180 million tonnes of industrial minerals are produced annually, with estimated sales exceeding €10 billion (Wyart, 2015).

KAOLIN

Kaolin is an important class of industrial minerals which refers to a range of commercial china clay products consisting mainly of kaolinite. On account of its physical, optical, and chemical properties, kaolin is used in the manufacture of a broad range of products, including ceramics, paper, paint, plastics, rubber, pharmaceuticals, cosmetics, ink, sealants, adhesives, sanitaryware, glass fibre, toothpaste, animal feed, etc.. The wide range of kaolin applications points to a tradition of innovation and market research. New applications for kaolin are developed by tailoring relevant properties during a refining process while further upgrading may be achieved through a calcination process. This paper explores opportunities for application of geometallurgy by analysing kaolin extraction in the UK. Significant kaolin resources were formed in south-west England over time as a result of alteration of granite (Bristow, 1977). In its unaltered state, granite consists of various proportions of quartz, micas, and feldspars. Kaolinite is formed by decomposition of sodium-feldspar (albite), potassium-feldspars (orthoclase) and, under extreme conditions, mica. Kaolin deposits in the St Austell region of Cornwall, south-west England, are dubbed primary because kaolin is found in the location where it was formed.

{Figure 1}

Despite some variation in the type of granite (Figure 1), the St Austell kaolin deposit is of exceptional quality due to a culmination of favourable conditions (e.g. Psyrrillos et al., 1998,

Bristow et al., 2002); they have been worked for over 250 years. Current annual production is still about 1 million tonnes (Cornwall Council, 2015). In recent years, the volume of production has declined as a result of developments in the marketplace. This creates pressure on the UK kaolin industry to innovate, increase the efficiency of resource extraction and develop new kaolin products and applications.

PHYSICAL PROPERTIES

In product form, kaolin is a free-flowing, non-abrasive bright white powder with a high proportion of particles with a size below 2 μm . Kaolin particles have a quasi-hexagonal, “platy” shape which expresses the underlying clayey structure consisting of layered sheets of aluminosilicates (Pyrillos et al., 1999). Both particle shape and size distribution of kaolin are important properties for its commercial application. Other important physical properties of kaolin are its relatively low surface area, low absorption capacity, low viscosity at high solid concentrations (providing good coverage), and its low conductivity for heat and electricity (Prasad, Reid and Murray, 1991, Murray, 2000). An important aspect of the commercial value of kaolin is its white colour and the brightness of its colour. Various ISO and DIN standards can be applied for determination of kaolin brightness. For example, ISO R457 prescribes illuminating a sample with light of wavelength 457 nm, which has a blueish colour, measuring the reflectance, and expressing the brightness as the percentage of the reflectance of an ISO standard at the same wavelength. In terms of colour, the appearance of kaolin may take on a yellow hue. Noting that the human brain appears to consider blue and yellow as opposite colours, the yellowness of kaolin can be inferred from the difference between the percentage reflectance at 570 nm (yellow light) and percentage reflectance at 457 nm (blueish light). Differences in colour may indicate variation of the mineralogy and chemical composition.

CHEMICAL PROPERTIES

The main mineral in a kaolin deposit is kaolinite, accompanied by varying proportions of quartz, unconverted feldspars, micas (e.g. biotite), other clays such as smectites (swelling clays such as montmorillonite), illite, as well as accessory minerals (e.g. tourmaline). Kaolinite occurs in a host of textures ranging from finely crystalline kaolinite, with a relatively low particle aspect ratio, to vermiform stacks of kaolinite (Pyrillos et al., 1998). In pure form, kaolinite is represented by the chemical formula $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ or more intuitively, $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$. With kaolin applications, it is often relevant to understand the proportion of aluminium which is soluble. Furthermore, the presence of other elements may influence the kaolin colour and brightness. Impurities can include iron oxide (Fe_2O_3), potassium oxide (K_2O), magnesium oxide (MgO), sodium oxide (NaO), phosphorus pentoxide (P_2O_5), titanium dioxide (TiO_2), and trace metal oxides. Iron oxide (Fe_2O_3) can affect the colour of kaolin, imparting a reddish or yellowish appearance, and reduce the brightness. Potassium oxide (K_2O) can affect the behaviour of kaolin at elevated temperatures by creating a liquid phase. Although potassium is absent in pure kaolinite, it is present as potassium oxide and in associated minerals, notably micas such as muscovite and illite. While it is important to understand the distribution of impurities in kaolin, the collection and analysis of samples is time-consuming and potentially costly. For every project or operation, the sampling effort requires optimisation: an optimal sampling effort corresponds to the lowest cost associated with sample collection, preparation, and analysis plus the cost of incorrect decisions based on sampling. Both the sampling effort and the

combined cost of sampling and incorrect decisions can be reduced through innovation (Figure 2).

{Figure 2}

An example of a step change in sampling practice of operations was the introduction of field devices fitted with sensors which can rapidly scan and analyse points on or even entire mine faces and benches. The advent of accurate, high resolution, and increasingly affordable sensors can quickly generate a wealth of data which is not restricted to chemical properties. The ability to measure and interpret a range of properties in the field creates opportunities for geometallurgy. To assess the potential of geometallurgy, its scope is defined in the following section.

GEOMETALLURGY

Geometallurgy can promote sustainable extraction of resources and increase resource efficiency by informing the optimal allocation of in situ resources in time. In pursuing this aim, successful application of geometallurgy requires:

- in situ spatial domain characterisation of types of ore from exploratory drillholes and geophysics,
- classification of ore types linked to specifications for various applications,
- analysis of the response of ore types to refining strategies,
- integrated planning of the extraction and refining of ore, and shipment of product to customers,
- optimisation of production from an economic, environmental, and social perspective.

These objectives appear to overlap, at least in part, with existing best practice in the mining industry. Where geometallurgy truly advances existing practice is by smart consideration and measurement of a broader spectrum of properties than the customary chemical grades. All properties of in situ ore which can affect the processing are within scope. While additional measurements could add considerable expense, emphasis is on smart application of geometallurgy. This endeavour necessarily promotes innovation in measurement, analysis, planning, and control within the context of a particular project or operation. In the next section, potential geometallurgy-driven innovations in upstream characterisation of kaolin are discussed.

IN PIT CHARACTERISATION

During evaluation of metalliferous deposits, grade-tonnage curves are routinely constructed to establish the tonnage of metal or ore at a given cut-off grade. With kaolin deposits, grade-tonnage curves could relate to trace metals present which may be of interest as by-products. For kaolinite itself, the classic notion of grade is unwieldy as routine laboratory determination of kaolinite is relatively complicated. A more accessible characteristic is the distinction between soft clay and hard granite phases. In the field, visual inspection gives qualitative insight into the local proportion of clay. Systems for classification of visual observations have emerged. Table 1 shows an example of a system of 'grade' classes informed by the proportion of clay, which is expressed in terms of granite alteration.

{Table 1}

It is interesting to note that the degree of alteration correlates with rock strength and density, which decrease as the proportion of clay increases (Henscher et al., 1990, Coggan et al., 2013). These well-established correlations point to existing routine application of geometallurgy in kaolin extraction. This role may expand through innovation in-pit face and bench characterisation techniques. Photogrammetry, which is the science of taking measurements from photographs, and Light Detection and Radar (LIDAR) technology make rapid scanning of mine faces a reality. Interpretation of mine survey data has numerous uses. For example, periodic surveying of the mine reveals the locations and volumes of ore extracted during a given period. Analysis of slope angles informs assessment of slope stability and safe mine design. Further interpretation yields insight into the orientation of structural features such as fractures, veins, faults, discontinuities and joint sets. With kaolin, insight into the spatial distribution of structural features is potentially relevant for grade control: a low density or even absence of structural features in the pit wall suggests a high degree of kaolinisation, and vice versa. Hence, advances in characterisation may inform monitoring of the in-pit kaolin grade, expressed in terms of an indicator which follows an engineering classification system (Table 1). This approach, which improves control, enhances the existing application of geometallurgy in kaolin extraction. A further attribute of mine survey data is the spatial distribution of colour, captured through the reflectance. Measurement of colour could indicate the presence of impurities such as iron oxide in worked pit faces. It should be noted that, in the field, weather conditions may influence colour and brightness measurements. To reduce weather-related effects, measurement of reflectance outside the visible light spectrum is of interest.

{Figure 3}

Figure 3 shows that various minerals found in the southwest UK kaolin deposits have distinct spectral signatures in the Near Infrared (NIR) wavelength range (700 – 2500 nm). Kaolinite shows overall high NIR reflectance which makes its characteristic absorption bands stand out. The double absorption bands ('doublet') around 1400 nm indicate the hydroxyl group (-OH), while the doublet just below 2200 nm distinguishes the hydroxyl group in terms of location in the mineral: the features at 2150 nm and 2190 nm are related to Al-OH, respectively Si-OH bonds. Kaolinite absorption bands will vary in depth as a function of the mineralogical composition of a neighbourhood (Iyakwari and Glass, 2014). Hence, kaolin grade class is obtained after suitable calibration based on mixtures of pure minerals in various proportions. Note that kaolinite content may be obscured if minerals which have absorption bands at similar wavelengths as kaolinite are present in appreciable quantities. This includes minerals such as muscovite, montmorillonite, and hallyosite. The presence of iron oxide may affect the calibration of kaolinite grade because its low reflectance across the NIR wavelength range masks absorption bands of other minerals. Close to the visible spectrum of light, iron oxides such as hematite and goethite display a characteristic absorption band around 900 nm (Townsend, 1987). Properly calibrated, the depth of this band may provide an estimate of the iron content. Finally, water has NIR absorption bands at wavelengths of 1430 nm and 1900 nm, with the latter being very pronounced. While moisture is controllable in the laboratory, NIR field measurements need to account for the influence of moisture. Moisture in the pit can be assessed using a thermal infrared camera,

which generates a temperature profile of the pit face by scanning at wavelengths between 9000 – 14000 nm. In the Cornish setting, it is postulated that colder zones correlate with the main joints which act as conduits for cooler groundwater. When the thermal image is draped over the 3-D laser point cloud, it is possible to orientate the principal kaolinised features of the face. This illustrates that field deployment of a NIR sensor benefits from introduction of positional dependency through combined application with photogrammetry or LIDAR. Additional sensors can be mounted on field surveying equipment using a panoramic camera head ('nodal ninja'). A further development is the option of performing scans using Unmanned Aerial Vehicles (UAVs). It should be noted that in-pit measurement of optical or NIR properties necessarily provides surface data. Geophysical techniques have the potential to generate data inside benches within kaolin pits. Due to pronounced differences in kaolin and host rock properties and sensitivity to water, in-pit electrical conductivity and induced polarisation measurements can provide spatially-informed data on the kaolin grade class, as well as the groundwater distribution, within a bench. Combined data from in-pit characterisation techniques informs short-term pit planning and downstream processing. This approach potentially saves time and reduces routine use of the laboratory. However, the discussion also illustrates some challenges associated with in-pit characterisation which, in order to realise the full potential of geometallurgy, need to be addressed with innovative approaches.

KAOLIN EXTRACTION AND REFINING

Kaolin extraction traditionally involves developing a pit in which high-pressure water jets ('monitors') are directed at the pit face. Washing the pit face creates a slurry which flows to the pit floor, from where it is pumped out of the pit. This wet mining technique is particularly suitable for working very high-grade deposits. When working lower grade kaolinite deposits, conventional blasting may prove necessary to break down the granite matrix. Following blasting, extraction may proceed through conventional wet mining or, to improve process control, by hauling broken ore to designated clay washing areas or facilities which may reside outside the pit. The latter approach creates a dry mining environment at the pit face and offers better control of the extraction process. The slaked clay is upgraded during a series of refining steps, in which the larger sand and gravel particles and mica are removed from the kaolin with physical separation techniques. The next step is to treat impurities in kaolin. Iron may be present in kaolin in various forms: as pure iron oxide (Fe_2O_3), kaolinite with iron absorbed on the surface or matrix, and in associated minerals such as biotite ($\text{K}(\text{Fe},\text{Mg})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$) (Dominy, 1993). When individual particles contain a sufficiently high concentration of iron, these can be physically separated by a high-strength magnet or by selective flocculation. Otherwise chemical reduction of Fe(III) to colourless Fe(II) or chemical leaching at low pH (<3) may be required (Gonzalez and Ruiz, 2006). In order to allocate the most appropriate treatment route, the measurement of colour merits further attention.

COLOUR CHARACTERISATION

A common approach for characterising colour is through a set of Red-Green-Blue (RGB) scores ranging between 0 and 255. When all RGB scores equal zero, a black colour is observed, while all RGB scores equal to 255 corresponds to a white colour. An option to infer kaolin brightness is based on a weighted sum of RGB scores. In line with the sensitivity of human vision, the largest weight would be allocated to the green score (> 0.5), followed

by weighting of the red score (between 0.2 and 0.3) and least weighting of the blue score (< 0.2). This empirical approach does not appear to preserve the link between kaolin properties and human observation. Evidence suggests that the brightness or lightness of colour is an independent variable of colour alongside variables for hue, which indicates the tone of colour, and saturation, which represents the intensity of colour. Adopting this approach, colour can be characterised by Hue-Saturation-Value (HSV) scores, where Value represents the brightness or lightness. Yet HSV scores are transformations of RGB scores, which vary with the device they were created on. The CIELAB colour system, launched by the Commission Internationale de l'Eclairage (CIE) in 1976, is commonly referred to as Lab or $L^*a^*b^*$ system. It features device-independent colour characterisation using three colour variables: L^* , a^* , and b^* . The concept builds on the discovery that the human brain distinguishes between light and dark, red and green, and blue and yellow colours. Hence, L^* expresses the lightness, where $L^* = 0\%$ corresponds to perfect darkness and $L^* = 100\%$ to pure whiteness, while a^* characterises the red/green hue and b^* represents the yellow/blue shade. To a standard observer, defined by CIE in 1931 as the average perception of a persons with normal vision, positive values of a^* indicate more red and negative values of a^* indicate more green. Positive values of b^* indicate more yellowness and negative values point to more bluishness. Although L^* may not represent absolute brightness because the upper value of L^* is defined by a reference illuminant (see e.g. discussion by Ocean Optics, 2016), an important advantage of the $L^*a^*b^*$ system is that the variables correlate more uniformly with observed colour variations than RGB and HSV variables.

{Figure 4}

For kaolin, application of the $L^*a^*b^*$ system offers the advantage of characterising the whiteness of kaolin directly through L^* and the colour effect of impurities through a^* and b^* . The $L^*a^*b^*$ system is particularly suited to consider the form in which iron is present. The colour of kaolin which contains iron varies between a red and a yellow hue. Noting that iron oxide by itself is a red pigment, it is postulated that a red hue, characterised by a^* , indicates free iron. Furthermore, the yellow hue, characterised independently by b^* , suggests a different form of iron; it is postulated that this indicates iron absorbed in the kaolin. Hence, measurement and interpretation of a^* and b^* during resource modelling or upstream in-pit characterisation assists selection of the most appropriate downstream refining process.

MINE OPTIMISATION

In an ideal situation, it could be assumed that a resource constitutes a sharply delineated volume of ore which is homogeneous in terms of its properties. This is rarely the case in practice: while properties are determined by the geological setting and history, variation will occur between deposits and within a deposit. Understanding this variation is essential for many aspects of mine planning and reporting. Starting point is modelling the resource on a number of length scales, with the smallest scale likely to correspond to that of the Selective Mining Unit (SMU). The SMU defines the smallest volume of ore on which ore/waste classification is performed (Sinclair and Blackwell, 2002). With kaolin, the usefulness of the SMU definition is influenced by the mining method: dry mining offers more control than wet mining. Mine optimisation is specifically concerned with modelling the resource in terms of what is required to inform an integrated and optimised extraction and refining process. This

involves the process of matching demand for individual kaolin products with available kaolin resources. For a resource containing different types of kaolin, it is important to define representative properties of types of kaolin on the scale of SMUs and their distribution within the deposit. This requires analysis of the spectrum of raw kaolin properties in the deposit with consideration for assorted product specifications. As illustrated by the treatment of iron present in raw kaolin, the cost of processing a particular type of kaolin to a desired quality can vary. For each type of kaolin, the response to, and associated unit costs of, refining options requires analysis, either through analysis of historical data, targeted laboratory experiments, or process simulations. A tentative economic optimisation seeks to minimise the processing costs by allocating high quality raw kaolin to production of high value speciality kaolin and assigning lower quality raw kaolin to bulk products with lower specifications. Figure 5 shows a conceptual description of scenarios in which different qualities of ore are mined and allocated to customised refining routes to create products of different specifications. In terms of kaolin resource efficiency, the optimum scenario corresponds to perfect matching of ore type to product type through an appropriate refining process.

{Figure 5}

Note that the size of, and access to, individual resources of different types of kaolin, control of extraction, as well as unit product values, also influence the optimal allocation of resource to processing. Innovation is required to integrate geometallurgy fully into mine optimisation practice. While geometallurgical variables are often non-grade and non-additive properties, the process of assigning geometallurgical values to SMUs may differ from conventional approaches. The following section discusses geostatistical practices for estimation in deposits.

GEOSTATISTICS

Ore characterisation traditionally commences with interpretation of samples obtained from drillholes. Geostatistical techniques such as kriging are then used to estimate properties at unsampled locations. Application of simple kriging makes assumptions, the most prominent being that the expected value of a property of interest within a geological domain is constant. It is, however, permissible that the measured property of interest varies within the domain. Evidence of this variation can be observed in measurements relating to samples drawn from the domain. The observed variation can, in part, be ascribed to the sampling process: a fundamental sampling error is unavoidable if the spatial distribution of the property of interest is not homogeneous on the scale of sampling. The sampling error expresses the difference between a sample analysis and the true value of the domain, while sampling is biased if the expected value of sample analyses differs from the true value. Assuming there is no systematic bias in the sampling process, the fundamental sampling error stems from the random selection of sample increments with different properties from a domain, which can be viewed as a collection of increments available for sampling. The overall sampling error increases during sample preparation in the laboratory, when a portion of the original sample is extracted for analysis, and during analysis itself. It should be noted that the sample preparation error can be controlled, for example by reducing particle size through grinding in between stages of riffing or similar sample size reduction processes. Likewise, the sample analysis error can be controlled as sources of error in the

laboratory are relatively well-defined. While the fundamental sampling error is linked to sample size and necessarily indicates short-range variability, the variability on any length scale is an expression of the cumulative geological history of the deposit. For practical reasons, the sampling error is disregarded during estimation of unsampled locations - for a full discussion, the reader is referred to Cressie (1988). Simple kriging has the drawback of using an average value for the property of interest in a domain for estimation of unsampled locations ... to determine an average of the domain. This circular argument is avoided with ordinary kriging, which only assigns weights to measured values within a defined neighbourhood to generate an estimate at an unsampled location. The weighting applied to individual measurements is influenced by distances between sampled locations in the neighbourhood and the unsampled location to be estimated distances, as well as distances between the sampled locations themselves. The various distances and weights are captured in a system of linear equations. Prior to solving the equations to reveal the weights, all distances between paired points are converted into semivariances using variogram models.

VARIOGRAM MODELS

A variogram model, which is based on interpretation of measurements in the domain, only has limited physical meaning. For example, the popular spherical model assumes that the influence of any point on its surroundings is represented by a sphere about the point. Note that the diameter of this sphere equals the range of the variogram model. When the distance between two points is within the range, their spheres will overlap. The volume of overlap between their spheres relative to the volume of a single sphere is a measure for their similarity. Hence, no overlap implies that the semivariance is equal to the sill of the variogram model, while a degree of overlap causes the semivariance to decrease (Figure 6). When the locations of two points coincide, the overlap is complete and the semivariance should be zero.

{Figure 6}

Noting that the model semivariance is derived as an average value of paired measured points, a zero semivariance at distance zero implies that the spherical model caters for perfect reproducibility of sample analyses in the laboratory. In other words, the sample preparation and sample analysis errors are assumed to be negligible. In a laboratory, this will be easier to achieve with chemical analyses than with measurement of geotechnical properties. Extrapolating the trend in measured semivariance to distances smaller than the closest measured points often suggests a non-zero semivariance at zero distance. When this is the case, a constant representing the nugget effect may be appended to the spherical model. Note that using a sphere of influence implies a lack of directional preference. It is, however, possible to accommodate some form of geometric anisotropy, which is observed when the range varies with direction while the sill of the variogram model is constant. With an ellipsoid, two ranges are defined about the central point. The ellipsoid is then oriented to align its longer range with the strike, in the direction of maximum continuity, while the shorter range applies to a circular cross section perpendicular to the strike. The relationship between the semivariance and the distance between two points, given by ellipsoid centres, is again informed by the volume of overlap, in this case between two ellipsoids oriented in the same direction. The resulting relationship is identical to that provided by the spherical

model when the distance is transformed using the ratio of the longest and shortest range (Figure 7).

{Figure 7}

For more detail on anisotropy, the reader is referred to Wackernagel (2010). To account for anisotropy, the geologically-informed orientation of ellipsoids relating to individual points within a domain may lead to better expression of the similarity between points. It should be noted that, with decreasing distance, the overlap of ellipses with different orientation defines a nugget effect whose magnitude depends on the relative orientation. Although the nugget effect should not exhibit a directional preference, it draws attention to an issue relating to non-chemical properties such as optical and geotechnical variables. With these properties, the orientation of a measuring device towards a sample can influence the measurement result itself. When modelling a kaolin deposit, many in situ kaolin properties are either indicators or proxies for grade, or non-grade properties. Improving the physical relevance of variogram models for non-grade variables could open up new avenues leading to better estimation of geometallurgical variables in SMUs or delineation of geometallurgical domains in a deposit.

CALCINED KAOLIN

Although the preceding discussion has largely focussed on measurement, interpretation, and planning, reduction of energy consumption is an important aim of geometallurgy. With kaolin production, the majority of energy is consumed towards the final stages of refining, where kaolin product is dried through a series of unit operations. Following dewatering with a filter press, the moisture content is reduced further through thermal drying to produce a dry powder for shipment to customers. For some applications which require kaolin with exceptional brightness, higher hydrophobicity and dielectric character, improved light scatter and hardness, a further processing stage is required (Prasad, Reid and Murray, 1991). This involves calcination of kaolin, achieved by briefly heating kaolin to temperatures of around 1050°C. During calcination, any residual organic matter is burnt off and kaolin undergoes a phase change, forming metakaolinite. Agglomerates of kaolin formed during calcining need to be milled afterwards. There are various applications for calcined kaolin products, which is chiefly used as a filler in paint (replacing titanium dioxide) or in rubber products. The calcination process consumes about 85 % of the energy associated with the extraction and processing (pers. comm. Imerys Minerals Ltd). To ensure that energy consumption is minimised for production of different types of calcined kaolin, development of an innovative, integrated approach to kaolin extraction, refining and control of the calcination process is under investigation in the STOICISM project, a collaborative research project led by Imerys Minerals Ltd.

CONCLUSION

Geometallurgy promotes the smart use of non-renewable resources through better allocation of the resource to processing options and products. This required integrated analysis and control of the entire mining chain, influencing the characterisation of the deposit, mine planning, process control, waste utilisation, and energy use. Innovations in the field of sensors and data processing are helping to shape the potentially far-ranging implications of geometallurgy.

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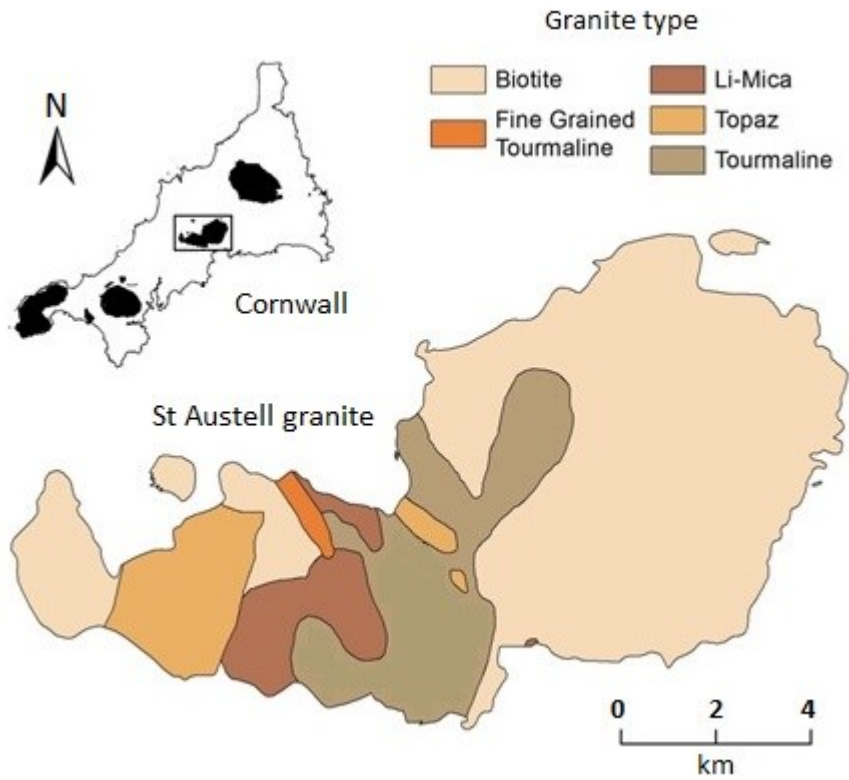


Figure 1: Distribution of granite types in the St Austell pluton (adapted from Psyrrillos, Manning and Burley, 1998).

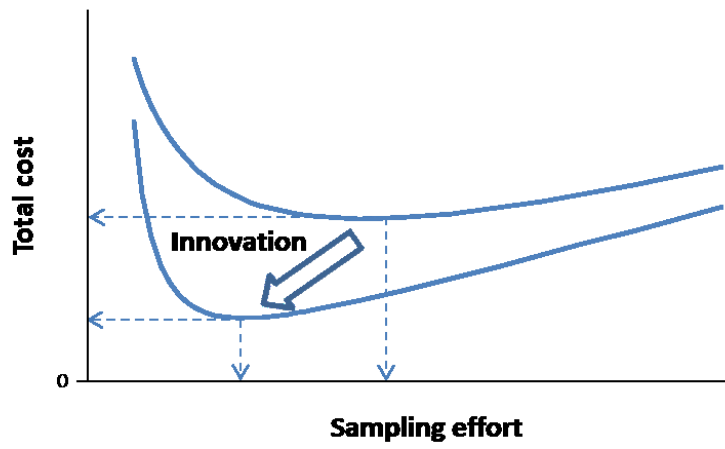


Figure 2: Graphical optimisation of sampling effort through innovation.

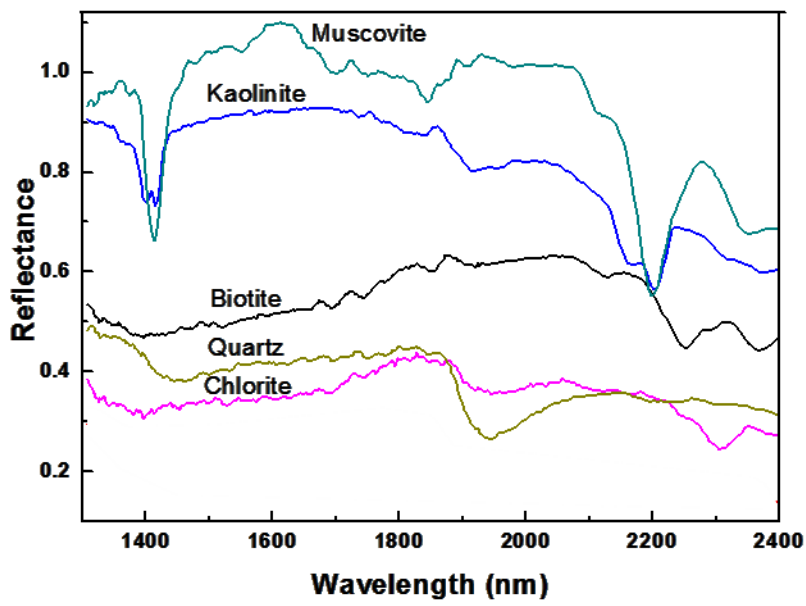


Figure 3: NIR spectra of selected minerals found in kaolin deposits (Iyakwari and Glass, 2013).

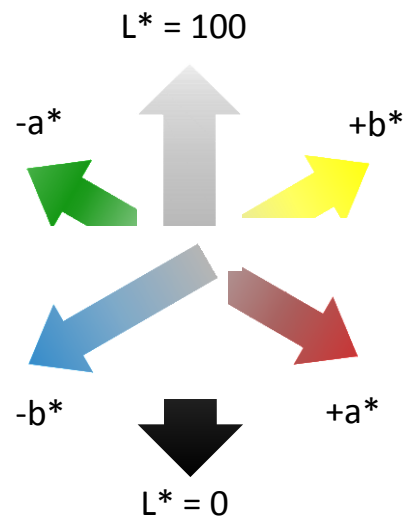


Figure 4: Schematic of L*a*b* colour system.


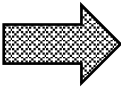
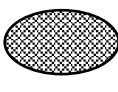

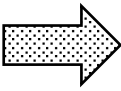
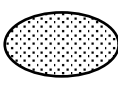

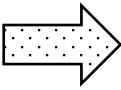
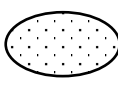

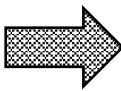
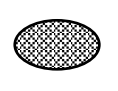

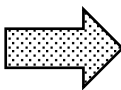
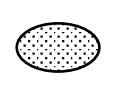

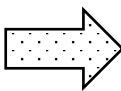



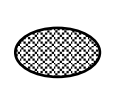


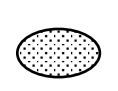

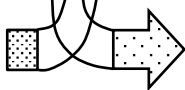
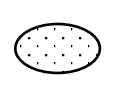
	Quality of ore	Ore	Process	Product	Product specs
Optimal process allocation of well-characterised resource with controlled extraction	High				High
	Medium				Medium
	Low				Low
Sub-optimal process allocation due to poorly characterised resource and/or lack of controlled extraction	Low				High
	High				Medium
	Medium				Low
Sub-optimal process allocation due to lack of controlled refining or processing	High				High
	Medium				Medium
	Low				Low

Figure 5: Optimisation of the efficiency of resource utilisation

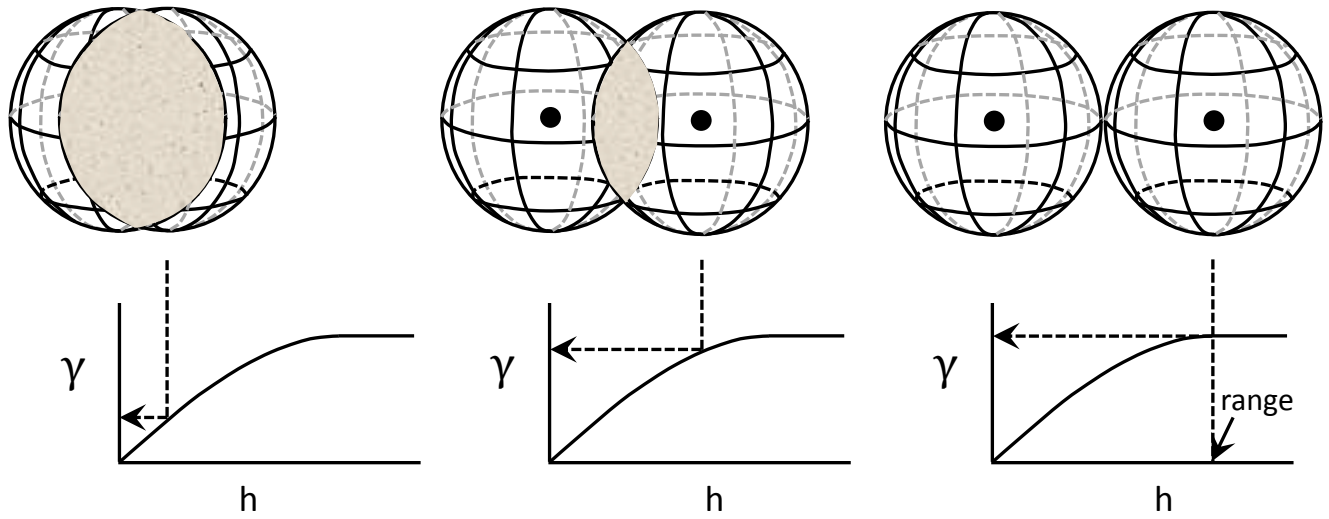


Figure 6: Spherical (semi)variogram, showing the increase of the semivariance, γ , coupled to the decrease of the intersecting volume of two spheres, as a function of the distance, h .

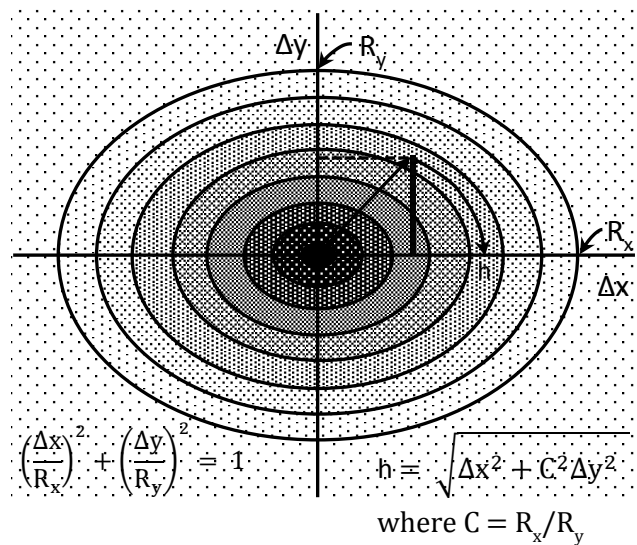
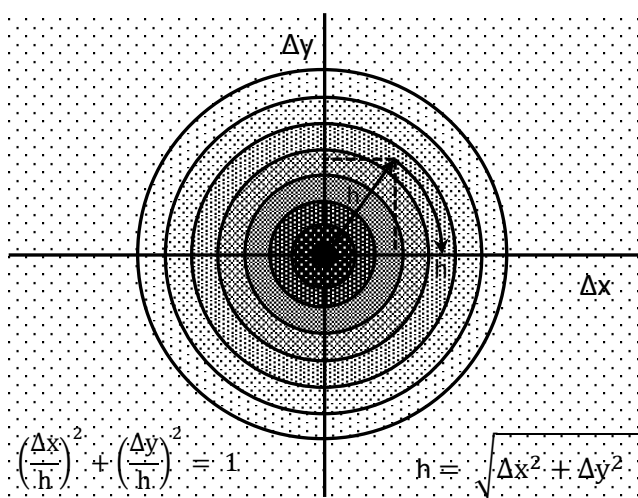


Figure 7: Determination of the distance, h , between pairs of points from Δx and Δy (2-D) for an isotropic variogram (left) and a variogram with geometric anisotropy (right).

Table 1: Classification of granite alteration (Anon, 1995).

Grade class	Classification	Description	Rock strength
I	Fresh rock	No visible alteration	
II	Slightly altered	Slight discoloration and weakening	Schmidt hammer 'N' > 45
III	Moderately altered	Considerable discoloration and weakening	Schmidt hammer 'N' 25 – 45
IV	Highly altered	Large pieces broken by hand	Schmidt hammer 'N' 0 – 25
V	Completely altered	Geological pick penetrates, slakes readily in water	Hand penetrometer 50 – 250 kPa