USING STRUCTURAL FEATURES TO TARGET KAOLIN DEPOSITS IN SOUTH-WEST ENGLAND

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Kaolin formation within the granite pluton at St Austell, Cornwall has occurred from the dissolution of feldspar crystals in the presence of alteration fluids. This alteration is shown to increase upon proximity to pre-existing structural features, such as veins and fractures, as they have provided a flow-path through the impermeable host rock. At major structural features, such as faults, the density of fractures allow for a well-connected flow-path, significantly increasing fluid volume, speed of flow and length of exposure - all of which contribute toward intense kaolinisation and improved grade of the final product. Due to this strong spatial relationship, it is suggested that computer-based methods using discrete fracture networks may be employed to target drilling and concluded that smart exploration of primary kaolin deposits is feasible.

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INTRODUCTION

Kaolin is the commercial term used to describe a white, industrial clay composed largely of the mineral kaolinite ($Al_4Si_4O_{10}(OH)_8$). Just over 1 million tonnes of kaolin are produced annually from the St Austell granite pluton in South-West England (Bide *et al.*, 2015) and are utilised in applications ranging from paper and ceramics to ink and pharmaceuticals. Production levels have steadily decreased in recent years (Figure 1), attributed to competition within the Western European paper markets and substitution (Cornwall Council, 2013).

This increased competition within the global market has reduced profitability, with many companies responding with corporate restructuring and cost-saving production strategies. Focus has shifted to Brazil, where enormous kaolin deposits and low production costs are more cost-effective in spite of additional shipping costs (Cornwall Council, 2013). Whereas the Brazilian deposits are secondary (transported away from their original location by water), the kaolin located within the St Austell granite is primary, formed from the in-situ alteration of feldspar crystals by convecting fluids (Brown, 1953; Fuge and Power, 1969). Matrix permeability within these igneous deposits is restricted by the interlocking, crystalline nature of the grains, with global permeability controlled by the presence of fractures and cracks which help channel the fluids through the rock mass. The kaolinisation at St Austell is of a particularly advanced nature, with over 50% of the pluton showing some degree of alteration. The western extent hosts the bulk of high-grade deposits and also shows the highest intensity of fracturing (Alderton and Rankin, 1983). These fractures, along with other structural features, such as veins and faults, have allowed alteration fluids to collect and circulate, with their interconnectivity determining the flow rate, exposure length, and pervasion of fluids within the pluton (Exley, 1964).

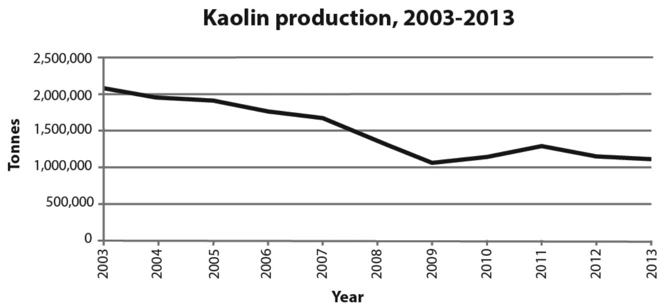

Figure 1. *Kaolin production in tonnes over a ten year period (British Geology Survey, 2009; Bide* et al.*, 2015).*

This paper aims to investigate the relationship between fracturing and kaolinisation. It is proposed to use discrete fracture networks (DFNs) to target drill-campaigns, shifting the focus of cost-saving efforts to the exploration (rather than production) phase. As this method is particularly suitable for primary deposits, where alteration has remained in-situ, it could help ensure that Cornwall remains at a strong position in the global market.

KAOLINISATION

Formation

The alteration of albite (Na) and orthoclase (K) feldspars into kaolinite by alteration fluids is identified as one of the last mineralisation episodes within the St Austell pluton (Psyrillos *et al.*, 1998). Often montmorillonite (a smectite clay group member) is considered to be an intermediate assemblage, with field samples of montmorillonite at St Austell often appearing to be kaolinising (Bristow, 1977).

As such, montmorillonite often appears within partially kaolinised deposits (Scott *et al.*, 1996; Psyrillos *et al.*, 1998; Ellis and Scott, 2004). Petrographic and geochemical investigation by Psyrillos *et al.* (1998) concluded that pure kaolinite (Grade V) is only found where dissolution of both albite and orthoclase feldspar is complete. During the early stages of the chemical reaction albite is altered preferentially due to its higher solubility (Exley, 1976), releasing excess Na^{+} ions which are thought to become incorporated temporarily as sodium-montmorillonite, subsequently disappearing as kaolinisation progresses (Exley, 1964). Veins and fractures are often surrounded by mineralisation 'halos' with maximum alteration (pure kaolin) closest to either edge (Exley 1964; Bristow, 1977), graduating outwards to a mixture of kaolin and montmorillonite (Psyrillos *et al.*, 1998), finally reaching unaltered granites where alteration fluids were unable to penetrate (Figure 2).

The presence of montmorillonite is not detrimental to the clay industry. For ceramic manufacturing, it is the physical properties which determine the quality of the kaolin blend. The presence of smectite increases the clay strength and it is highly sought after by the tableware, bone china and porcelain industries (Scott *et al.*, 1996). In contrast, kaolin blends intended for paper manufacturing should not contain any smectite. By defining the distribution controls of fully and partially kaolinised granites, it becomes possible to differentiate localities during exploration, in order to plan for appropriate future exploitation.

A major source of disagreement in the scientific community is whether the alteration fluids are hydrothermal in origin, or whether they may have been meteoric. This paper focuses on the transport of fluids rather than their origin, but field and laboratory evidence from various authors suggests that the kaolinite deposits seen at St Austell cannot have occurred from just one alteration environment, with many suggesting influence from both. For a more comprehensive discussion, the reader is directed, in particular, to Alderton and Rankin (1983), but also to Bristow (1977, 1993), Sheppard (1977), Exley (1958, 1976), Bray (1980), Bottrell and Yardley (1988), and Psyrillos *et al.* (1998, 2003).

Spatial controls

A very close spatial relation exists between kaolinisation and zones of previous, high-temperature hydrothermal events such as greisenisation, tourmalisation and veining (Bristow, 1977; Charoy, 1981; Alderton and Rankin, 1983; Psyrillos *et al.*, 1998). These previous mineralisation episodes have utilised major joint and fracture sets to circulate fluids, and kaolinisation is no exception. Kaolinisation grade and permeability of the host rock increase significantly upon proximity to discontinuity features and intersections (Bristow, 1977, 1993; Psyrillos et al., 1998).

Consequently the large discontinuity belts created by fault movement ('shatter' zones) must be considered critical localities for exploration targeting. The density of the fracture network in these areas will have increased the volume of fluid, the speed of flow, depth of pervasion within the host rock and the length of exposure to late-stage alteration fluids. The idea of focusing on fault deformation zones is supported by the knowledge that kaolinisation at St Austell is confined between two major fault zones (Psyrillos *et al.*, 2003). It should be noted that fractures are scale-invariant, which implies that structures are self-similar. In practice, it is difficult to determine if an image of a fracture is microns or meters across in the absence of a scale (Turcotte, 1997). In a similar manner, alteration around a fracture is also scale-invariant, with penetration dependent on the scale at which it is studied; microns at the scale of a single feldspar or tens of meters across a fault. This links in well with the idea that the fractures are the major control of alteration, regulating the volume of fluid flowing through the rock mass over time. Fractures that are spaced further apart from the network will experience low fluid through-flow, and alteration will not progress. Conversely, a fracture that is part of a group (e.g. fault shatter zone) is more likely to experience a large volume of through-flow with regular recharge periods. Figure 3 demonstrates how these fracture groups will promote alteration of materials in the vicinity.

The characteristic 'trough' shape of kaolin deposits found at St Austell can also be explained by the presence of fractures and fault-zones; deeper fractures are often held together by

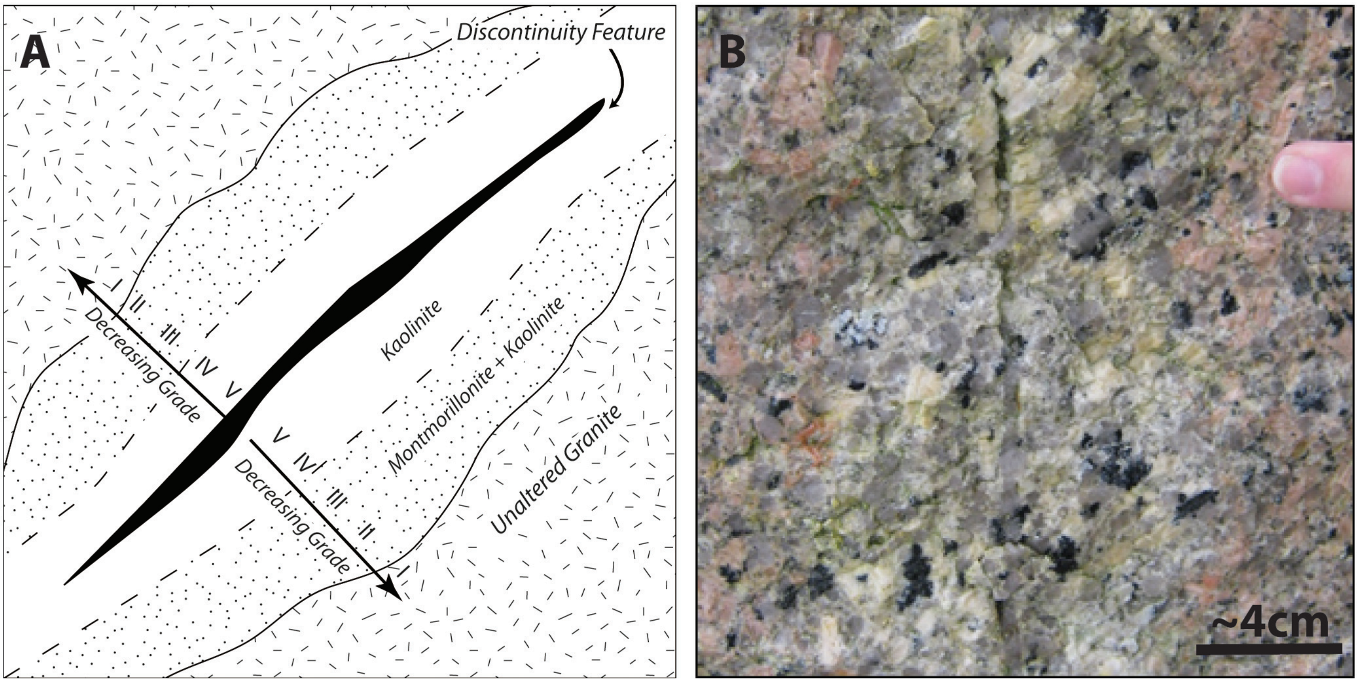

Figure 2. *(**a**) Alteration 'halos' surrounding a discontinuity feature. Grade of kaolinisation gradually decreases away from the centre of the feature (V>IV>III>II>I). (**b**) Wheal Remfry field example. The quartz vein in the centre is surrounded by white minerals which gradually become pinker.*

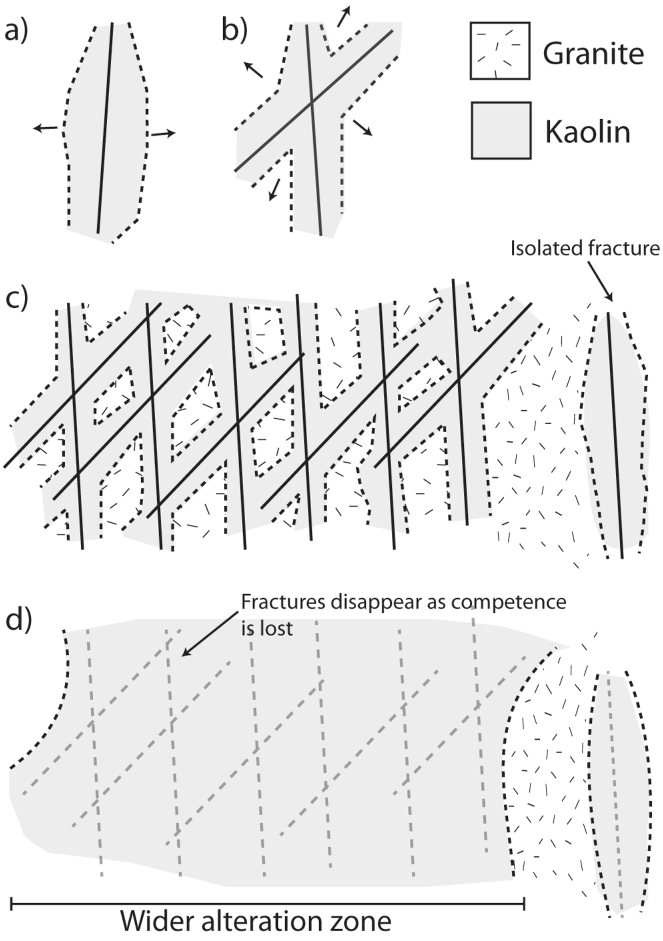

Figure 3. *(**a**) A single fracture produces alteration in lengthening direction. (**b**) At the point where two fractures intersect alteration occurs in both lengthening directions. (**c**) Across a fracture network alteration will occur at many intersections. Pieces of unaltered material will remain where alteration has not yet progressed. Isolated fractures will experience a smaller rate of alteration. (**d**) Alteration will reach a point where all granite has been affected. Alteration around isolated fractures will be narrower.*

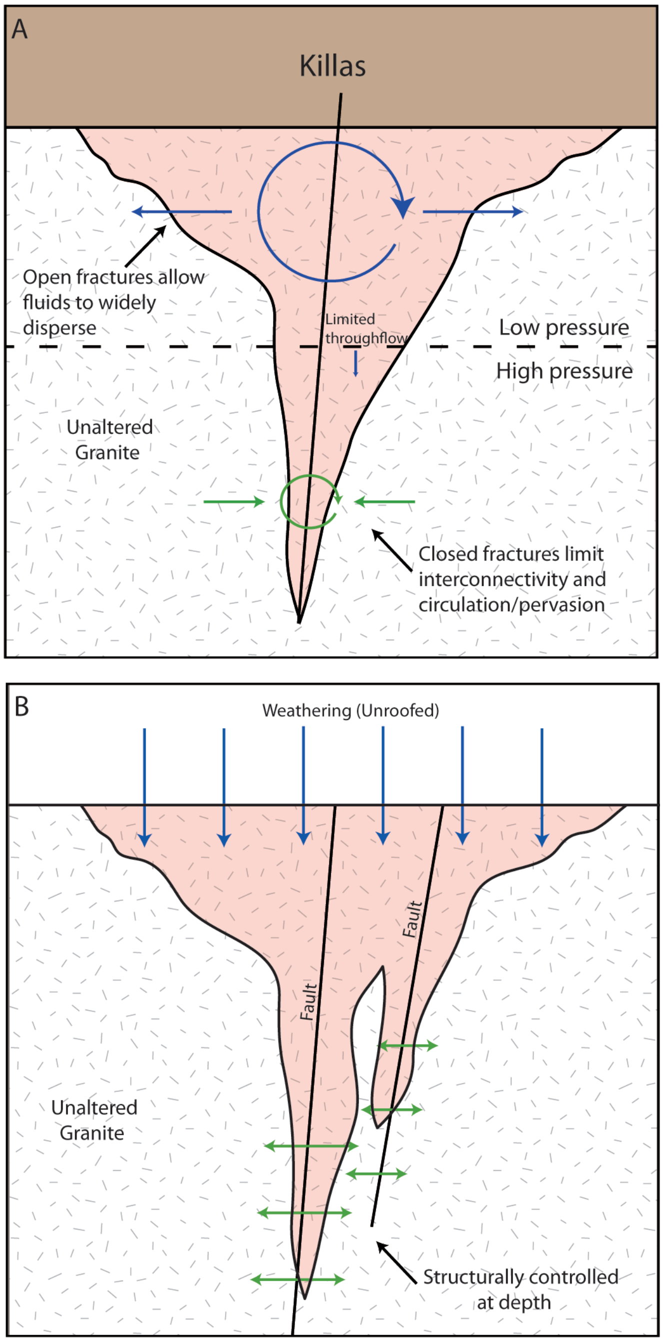

Figure 4. *(**a**) Internal pressures at depth keep fractures closed and reduce their interconnectivity and circulation (green circle). Fractures closer to the surface are more likely to be open and fluid will be able to pervade across greater distances (blue circle). Killas (Cornish country rock) prevents meteoric infiltration. (**b**) After unroofing the pluton is exposed to large amounts of meteoric water, greatly increasing kaolinisation at the shallow subsurface. It fails to penetrate to depth, where structural controls remain dominant (after Bristow, 1996).*

internal pressures whilst those closer to the surface remain open. In this manner, fluid circulation at the surface would have been more intense, allowing kaolinisation to affect a wider area (Figure 4a). It may also be notable that supergene weathering after unroofing will have exposed unfractured material to fluid-interactions at the surface, whilst at the base fractures and faults would remain the only control (Figure 4b) and would therefore be particularly useful for targeting within the deep-subsurface.

Discussion

The evidence gathered within this paper indicates that investigating fractures could help pinpoint kaolin deposits within St Austell. These structural weaknesses allow alteration to persist across a wide extent and it is highly likely that they are one of the main controlling factors in the expansive, commercially exploitable deposits found in this region. In particular, intersection of structural features must be a significant consideration for modelling of kaolinisation. Increased flow, recharge and pervasion at these localities will result in high-grade material, perfect for paper-based industries. From this knowledge, it would then be possible to estimate the likely position of medium-grade, smectite-dominated material, suitable for use in ceramics (Figure 5). By knowing the likely locations of soft, altered rock or hard, unaltered rock, this information may also be useful to inform excavation design and selection of drilling equipment.

To utilise this structural information for future modelling at St Austell we suggest that use of computer-based discrete fracture networks (DFNs) be considered. Software which can utilise fracture patterns and likely cluster zones are advanced,

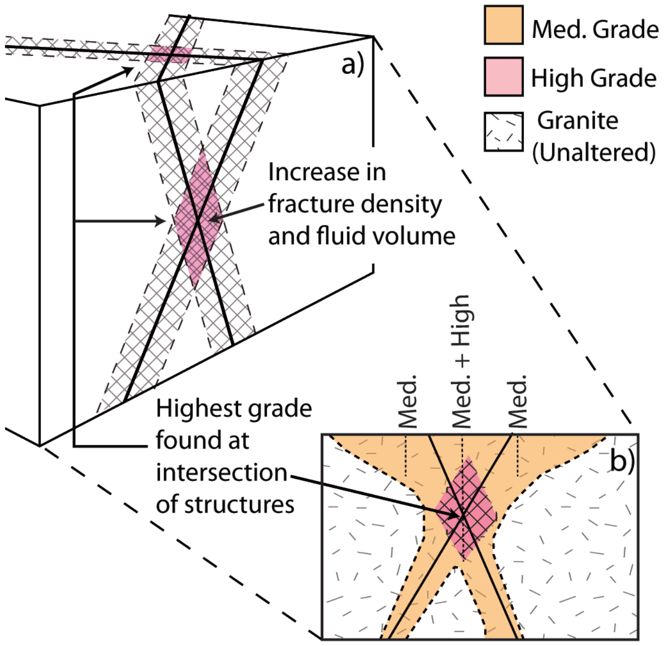

Figure 5. *(**a**) The intersection of two major features has created high grade material. (**b**) During exploration, grade can be estimated based on knowledge of where these features intersect at depth and drillholes (dotted lines) can be positioned accordingly.*

convenient tools to estimate quickly the connectivity, porosity and permeability of discontinuities, and can assist in locating kaolin targets. It is impractical to use fractures without first considering the tectonic movements which generated them. Field investigation can be utilised to determine tectonic movement and pressure of the surrounding geology and accurately define likely strain levels across different geological periods. This strain data can then be incorporated within a DFN to constrain the limits of brittle deformation and help assess the most likely areas of prolonged and intense fluid circulation by delineating the intensity of fracturing.

For industrial application, such techniques have the potential to generate significant savings on capital expenditure by positioning drillholes in profitable locations and by reducing the overall number of drillholes required. Note that the number of drillholes must be large enough to provide substantial, quality material for statistical analysis and to prevent bias, but implementing computer-based techniques to pinpoint exploration targets could ensure that the maximum information is obtained from the optimum number of drillholes. Although more intense field investigation is required with regards to the precise collection of fault, fracture, veining and tectonic data, it is likely to cost less than the expense of additional drilling.

Conclusions

Structural features within the St Austell pluton provided a pathway for alteration fluids through the impermeable granite. Hence, areas of kaolinisation are strongly linked with areas of faulting and fracturing, and intensity of alteration increases at the intersections of major discontinuity features. Structural features of the granite may be interpreted with computer-based methods involving the simulation of DFNs through time, with spatial distribution of porosity and permeability serving as a proxy for the degree of kaolinisation. This approach could help focus the exploration of kaolin resources to narrower zones, saving on the number of drillholes required to delineate the extent of the resource. Knowledge of the subsurface prior to drilling could also help excavation considerations such as drill-bit choice and pit design.

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