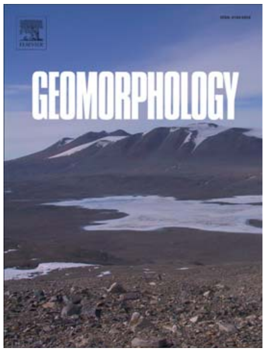

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Modelling the structural controls of primary kaolinite formation

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Abstract

An abundance of kaolinite was formed within the St Austell granite pluton of Cornwall, southwest England, by the hydrous dissolution of feldspar crystals. The permeability of Cornish granites is low and alteration acts pervasively from discontinuity features, with montmorillonite recognised as an intermediate assemblage in partially kaolinised material. Structural features allowed fluids to channel through the impermeable granite and pervade deep into the rock. Areas of high structural control are hypothesised to link well with areas of advanced alteration. As kaolinisation results in a loss of competence, we present a method of utilising discontinuity orientations from nearby unaltered granites alongside the local tectonic history to calculate strain rates and delineate a discrete fracture network. Simulation of the discrete fracture network is demonstrated through a case study at Higher Moor, where kaolinite is actively extracted from a pit. Reconciliation of fracture connectivity and permeability against measured subsurface data show that higher values of modelled properties match with advanced kaolinisation observed in the field. This suggests that the technique may be applicable across various industries and disciplines.

Keywords: Kaolinite, Discrete Fracture Networks, Structural Influence, Kaolinisation, 3D Modelling

1- Introduction

Kaolinite is found extensively across the St Austell granite pluton of southwest England, formed from the primary, in-situ hydrous alteration of Na-feldspar and K-feldspar (Brown, 1953; Fuge and Power, 1969). Closer inspection reveals that the degree of alteration varies locally (Coggan et al., 2013). There is unaltered granite, which shows no signs of kaolinite formation, and partially kaolinised granite with some kaolinite formation and intermediate assemblages. A deposit is considered to be fully kaolinised when kaolinite is the dominant mineral. The dissolution of feldspar and formation of kaolinite in the St Austell pluton is summarised with equations (1) and (2) (Psyrillos et al., 1998):

Na-feldspar:

$$2NaAlSi_3O_8 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2Na^+ + 2OH^- \quad (1)$$

K-feldspar:

$$2KAlSi_3O_8 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^+ + 2OH^- \quad (2)$$

Both equations result in the partial leaching of a silica by-product (Charoy, 1981) and an increase in hydrogen ion activity (Exley, 1976). As hydrogen ions dissolve within the circulating fluids, they corrode feldspar cleavage planes and allow ions to redistribute into silicate layers (Guilbert and Sloane, 1968). However, the change from feldspar to kaolinite is not as straightforward as the equations imply. Intermediate assemblages of alternative clay types, such as illite and smectite, are commonly found within partially kaolinised granites (Psyrillos et al., 1998, 2003; Bristow et al., 2000; Papoulis et al., 2004; Suringar, 2004). Papoulis et al. (2004) suggest that exposure length, permeability of the deposit, and the space available for the reactions are all factors that will influence the formation of clay. Partially kaolinised samples from St Austell are found to contain Na-montmorillonite, a smectite clay (Scott et al., 1996; Psyrillos et al., 1998; Ellis and Scott, 2004), due to preferential dissolution of plagioclase end-member albite (Exley, 1976; Psyrillos et al., 1998; Bristow et al., 2000).

Granite is relatively impermeable due to its interlocking crystalline texture. In order to create the wide expanses of kaolinite found around St Austell, alteration fluids must have utilised major discontinuity networks within the rock mass (e.g. joints, fractures, faults) to circulate. This is evidenced through the fact that the western zone of the St Austell granite is more fractured (Alderton and Rankin, 1983) and hosts many fully-kaolinised deposits. A more detailed discussion of the structural controls of kaolinisation across St Austell can be found in Tierney et al. (2015). It should be noted that current weathering profiles from granites across the globe suggest that kaolinite forms predominantly along joints, discontinuities and weaknesses (e.g. Fowler, 2005; Schiavon, 2007; Kadir and Kart, 2009; Borrelli et al., 2014; Ibrahim et al., 2015). This matches the observation that the degree of kaolinisation increases in proximity to structural features (e.g. Bristow, 1977) and their intersections (Richard Hooper, pers. comm., Sept. 2015).

This study examines the hypothesis that structural discontinuities within granite may be used as a proxy to pinpoint likely areas of advanced kaolinisation. The first study objective is to document major discontinuity sets and tectonic history at the chosen study for use in computer modelling. The second objective is to compare the computer simulation with known subsurface data. An additional objective is to assess the usefulness of the method across various geological disciplines. This study uses a combination of fieldwork and computer processing to achieve these objectives.

2- Regional Geology and Study Site

The Cornubian batholith of southwest England was emplaced during the Permian, c.290-270 Ma (Darbyshire and Shepherd, 1985; Bottrell and Yardley, 1988; Chen et al., 1993; Chesley et al., 1993) and comprises of six exposed plutons: Dartmoor, Bodmin, St Austell, Carnmenellis, Land's End, and the Isles of Scilly. While all plutons show some degree of kaolinisation, it is particularly prominent at St Austell, where over 50% of the pluton is altered to form the largest kaolinite deposit in the UK.

2.1- Tectonic History

The Cornubian batholith was emplaced into Devonian and Carboniferous sedimentary and igneous rocks which had been altered during the Variscan Orogeny (Scrivener, 2006). Extension of the Variscan mountains resulted in reactivation and inversion of previous major thrust faults (Alexander and Shail, 1995, 1996; Leveridge and Hartley, 2006) and thinned the crust. There is a strong correlation between emplacement of the granite and ENE–WSW extensional and NNW–SSE strike-slip faults (Alexander and Shail, 1995, 1996). Deformation along these structures continued after emplacement, fracturing and faulting the granite and surrounding country rock. Faults are often related to high permeabilities and the extent of highly-kaolinisation material in the St Austell pluton is considered to be roughly bounded by the Fal Valley and Par Moor NNW-SSE faults (Psyrillos et al., 2003).

Study Site

The relationship between structural controls and kaolinisation at St Austell is illustrated using data collected from Higher Moor, an active china clay pit operated by Imerys Minerals Ltd. Several different granite facies are noted at this pluton due to numerous intrusive episodes (Fig. 1). Biotite and topaz granites are thought to have intruded first, with significant differentiation and elemental partitioning leading to the later formation of a specialised tourmaline species (LeBoutillier, 2002). Tourmaline granites have been noted to produce high-quality kaolinised deposits because tourmaline crystals are resistant to alteration and do not liberate iron, which reduces staining (Manning et al., 1996).

In Higher Moor pit, there is visual evidence of both NNW-SSE and ENE-WSW steeply-dipping extensional faults (orientated at 160/87 and 052/85, respectively). One of these faults (ENE-WSW) displayed kaolinised gouge, reaffirming the influence of structural controls (Fig. 2).

3- Materials and Methods

3.1- Orientation Collection

Orientation data was collected from a mixture of methods. The application 'Fieldmove Clino' was utilised to gather individual measurement from exposures of unaltered granite. The application is very light and accessible, allowing mobile and tablet devices to function as substitute compass-clinometers. Data from a terrestrial laser scan (TLS) was also incorporated. Fig. 3 marks the localities where orientation measurements were taken. Georeferencing of the TLS could not be completed due to time constraints but the approximate location is marked on Fig. 3. Measurements were split into major discontinuity sets using Dips 6.0 (Fig. 4, Table 1).

3.2- Software

Move^{TM} (Midland Valley Ltd) is a structural modelling toolkit which contains advanced modules which can be used to model strain and create discrete fracture networks (DFNs). A key requirement of this investigation was to compare the computer simulated results with real, subsurface data. The case study at Higher Moor is very suitable because drillhole data was available which could be used to create a three-dimensional wireframe model of the subsurface. This model was compared with the computer simulation, enabling total analysis of the deposit to be completed within a single software package.

3.3- Strain Analysis

Representation of strain across Higher Moor forms the backbone of the fracture network and was estimated by modelling the granite body through time according to the fault mechanisms and movements collected from field observation and literature research. While the initial deposit model - based on drillhole data - was configured to the present day, fault movement was modelled in reverse and then calculated forward to obtain accurate strain estimations.

Although evidence may be subsurface, or have been removed during excavation, faults were assumed to extend to the outer limits of the deposit. During analysis of the wireframe model, a third fault was created which was based on the alignment of beds within the model. A summary of the fault data used for strain analysis is given in Table 2. The results of strain analysis were incorporated into a standardised geocellular model (block dimensions 20 m x 20 m x 20 m).

3.4- Discrete Fracture Modelling

DFN modelling is a method which incorporates the geometry and properties of individual fracture sets as factors controlling fluid flow and transport. The technique creates simulated statistical networks (Dowd et al., 2009) to solve the disparity between three-dimensional flow and two-dimensional fracture observations in the field. Modelling in three dimensions allows geologists to treat each fracture as a discrete entity irrespective of its - full or partial - connectivity, increasing the predictive power of the method (Zhang and Jeffrey, 2014). The method discretizes the area associated with each fracture to produce a large number of internal elements and arbitrary geometries (McClure and Horne, 2013). For Higher Moor, all major fracture groups within the model were set according to parameters listed in Table 3, with orientation and Fisher values set to those determined in Table 1.

Intensity was set to P32 (fracture area per unit volume) and was further restricted by the strain ratio of e1/e3 (i.e. the ratio of maximum/minimum strain). The ratio between e1 and e3 is relevant: in a cell which has experienced both high e1 and high e3, strain values will end up cancelling each other out (i.e. ratio=1) whilst a cell with high e1 and low e3 values will have experienced a higher degree of deformation (i.e. ratio>1).

Length, aspect and aperture measurements were not collected due to time limitations. Field observations are often inaccurate due to the inability to properly map fractures in all three dimensions. For this preliminary study randomised lengths were considered satisfactory, whilst an aspect ratio of 1:2 and an aperture proportional to the root length were considered to be reasonable constraints.

4- Results

Approximately 43,100 fractures were constructed, averaging 25 fractures per m^3. This network was developed for further connectivity analysis, assessing the extent to which fractures cross-cut one another (Fig. 5). This information was then used to assess permeability across the deposit, highlighting likely zones of greater fluid accumulation and flow.

Figs. 6 and 7 demonstrate the finalised DFN, connectivity, permeability and the three-dimensional wireframe model used for comparison and reconciliation. The network is dense across the majority of the deposit. The highest permeability is observed in the centre of the northern sector (Fig. 6, right). Reconciliation of the results with the 3D drillhole-based model shows that this high-value area matches well with the major occurrence of highly-kaolinised material. Kaolinisation is ranked in terms of grade on a scale of 1 to 5 using a ranking system adopted by Imerys Minerals Ltd, the operators of the Higher Moor site. Grade 1 represents unaltered granite and Grade 5 represents fully-kaolinised material. Results at the western extent suggest lower than expected values and Grade 4 material to the south was less pronounced than expected, suggesting potential interference. Note that anomalously low values around the edge of the geocellular model are due to the way measurements have been clipped to the cells.

5- Discussion

The results presented in the previous section demonstrate a good correlation between the simulated discontinuity network and the spatial distribution of kaolinite (Fig. 7). This suggests that structural discontinuities are a dominant influence on primary kaolinite formation and that they could be used as effective proxies to pinpoint likely zones of advanced kaolinisation within granite. The influence of structural controls may also be equally applicable to other clay assemblages (e.g. illite, dickite) as long as the structural influence persists. However, our study has only considered kaolinite formation within in southwest England and any utilisation of the method for alternative clays would require further validation.

Implementation of the proposed method is quick. It requires background knowledge of the investigation site, structural measurements and regional geological understanding, as well as a computer with high processing capability. Application of this method allows rapid pre-assessment of a study area and selection of sites for further investigation, saving time, effort and expenditure by ensuring that the maximum amount of information is obtained.

While the results are based on a single case study, there is the possibility that the results are coincidental. Detailed fracture measurements with regards to length or aperture are lacking. Vujevic et al. (2014) state that average fracture length is more important for convection analysis than the density, emphasising the need to collect these measurements when in-field. Obtaining this information may be difficult due to the inability to properly assess a fracture in three dimensions from an exposure. For localities with no exposure, various geophysical methods could be employed instead.

Greater confidence in the technique could be gained through further application of the method. Its use in similarly established kaolinised zones could provide additional reconciliation. To assess the sensitivity of the discontinuity network, a set of results can be generated by varying parameters in the software. Once enough conclusive data has been obtained, the uncertainty can be assessed. Although the software is not set up to perform a sensitivity analysis, each of the factors in Table 3 should be investigated to understand how variations may affect the results. The influence of block size on the geocellular model should also be explored.

The key benefit of the Higher Moor case study is demonstrating the application of the proposed method for mineral exploration. Kaolinite has been mined from St Austell for over two centuries. Currently, an estimated 1.1 million tonnes are produced annually from open cast pits across the St Austell pluton (Bide et al., 2015). Production has steadily declined over the past decade due to heightened competition within the global marketplace. Many consumers now opt for cheaper sources of kaolinite, such as those found in Brazil. The kaolin industry is now facing pressure to reduce costs, with many companies developing improved or altered production processes (Cornwall Council, 2013). In this challenging environment, we believe that the proposed method could generate savings during exploration, when capital expenditure (CAPEX) is commonly high. Furthermore, the search radius shown in Fig. 7 may be utilised to locate drilling targets. Only a small percentage of the existing drillholes at Higher Moor are within the current pit limits. Many of these also record unaltered material. Although these drillholes were necessary at the time of drilling to narrow each subsequent campaign towards the zone of high grade material, preliminary modelling using DFN simulation could have accelerated this process and created CAPEX savings. Additionally, the method is unique to granites, where kaolinite forms in-situ. It is not applicable for Brazilian deposits which are sedimentary (Souza et al., 2005) and where kaolinite has been transported away from its original source by water. The method is also likely to be inappropriate when investigating supergene weathering of granite in tropical regions, where infiltration of meteoric water will exert a strong influence on alteration.

Another application of the method is in geotechnical engineering. In situ clays cause reduced competence and a reduction in strength. Clay-rich zones have been known to cause large-scale landslides in places such as Hong Kong (Duzgoren-Aydin et al., 2002). Pinpointing clay deposits is therefore essential for assessment of slope stability. However, we do not intend this method to replace detailed geochemical analysis or detailed stability investigation. Most 3D modelling software cannot be used as a substitute for traditional investigations or statistical estimation. Furthermore, the existence of a 3D model will not make estimations 'more correct'. Instead we suggest that the method should be used to guide investigations towards structural trends at a locality and to identify likely alteration zones that would warrant more detailed investigation. It is notable that the method may also be applicable for studies in nuclear waste storage or geothermal energy utilisation in order to gain a robust understanding of fracture connectivity and fluid flow.

6- Conclusions

From our investigation we conclude that:

- Modelling major discontinuity sets via a computer simulated DFN gave promising preliminary results when matched with subsurface data. Regions of high network density and connectivity correlated well with known occurrences of highly kaolinised material at a case study site.
- Structural discontinuities are therefore useful indicators of alteration fluid pathways at sites affected by weathering or hydrothermal alteration. They may be used successfully as a proxy to locate areas within granite where kaolinite may have formed.
- The methodology could be utilised across a wide range of industries and disciplines. While the method is particularly useful for localising drillhole targets for mineral extraction at the case study site, the method also shows promise for geotechnical assessment and civil engineering projects.

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Competing Financial Interests

The authors declare no competing financial interests.

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Figures

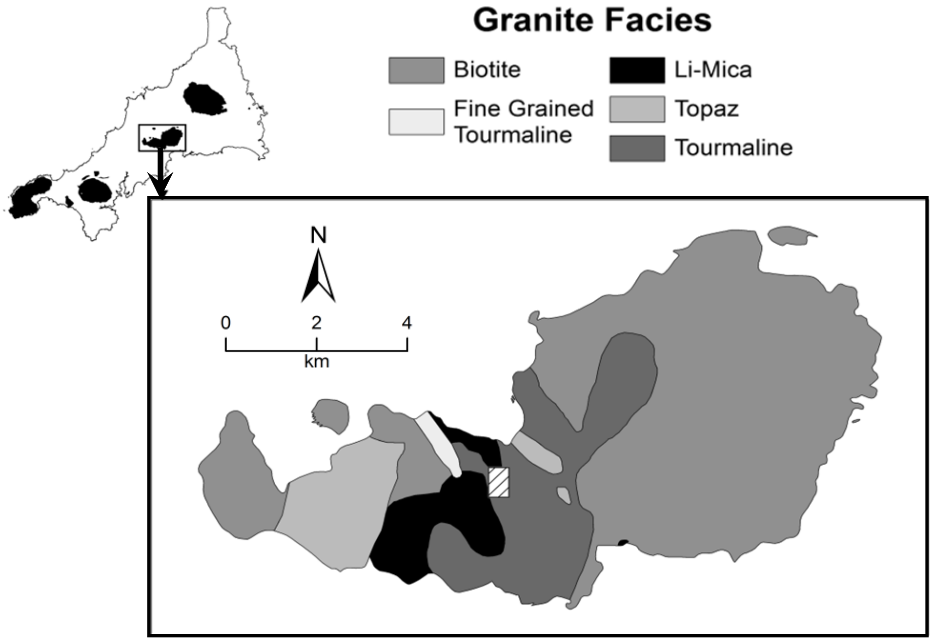


Figure 1- Granite facies present in the St Austell pluton (boxed area) within Cornwall (upper left). The location of Higher Moor pit is indicated by a striped box (not to scale). Based on Manning et al. (1996).

Figure 2- Example of kaolinised fault gouge at Higher Moor pit, St Austell. Black dashed lines indicate a fault and the white dashed lines indicate where background kaolinisation (potentially through late, supergene alteration) has stopped. The white arrow demonstrates how kaolinisation has advanced within the fault zone.

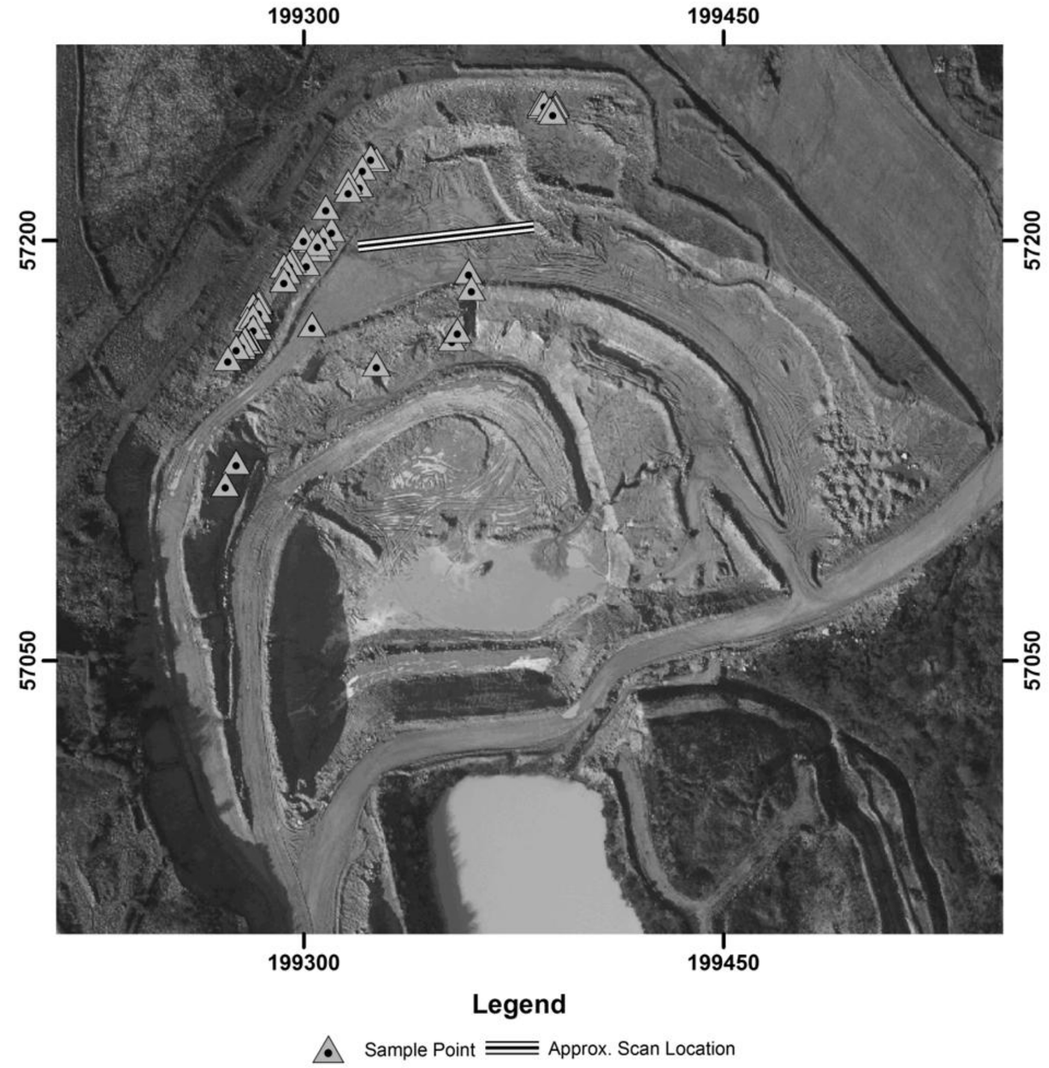


Figure 3- Recent satellite image of Higher Moor china clay pit. Sample points are localities where Fieldmove Cline measurements were taken. The approximate scan location is where measurements with the terrestrial laser scanner were made (not georeferenced in detail).

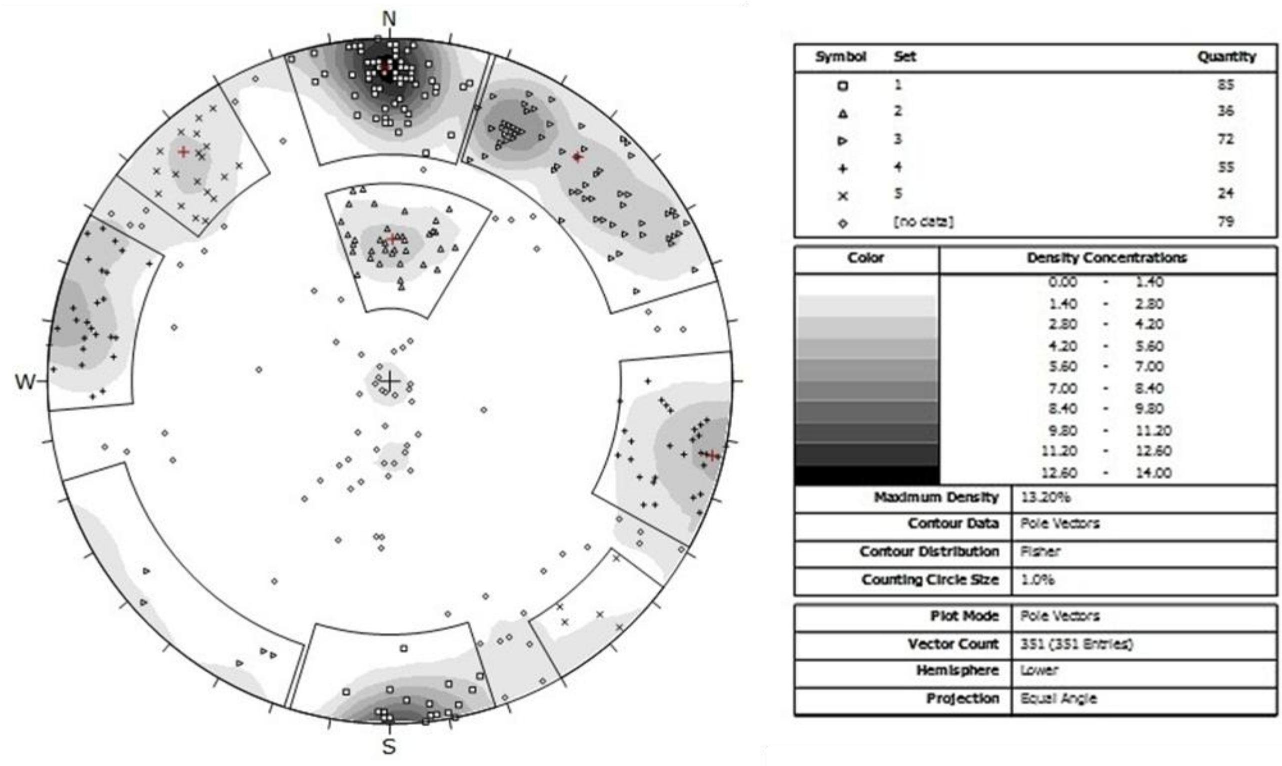


Figure 4- Stereographic projection of the orientation data collected from Higher Moor pit as poles. There are five dominant sets. *Lower hemisphere, equal angle projection. Dip/Dip Direction.*

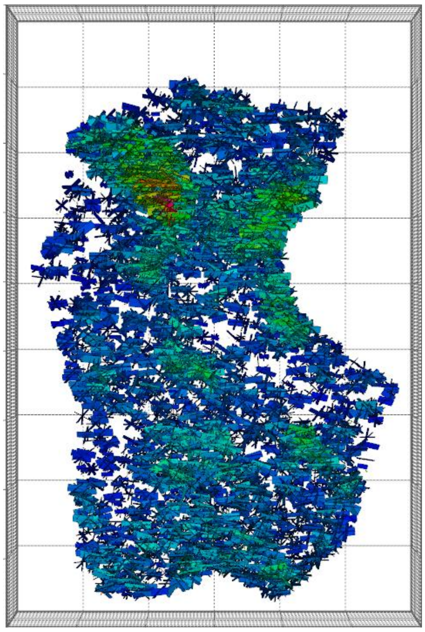


Figure 5- Connectivity degree of the fracture network. The highest degree of connectivity (red) is observed in the central northern zone of the network. This is likely to have promoted increased fluid flow which will, in turn, have led to a high degree of kaolinisation.

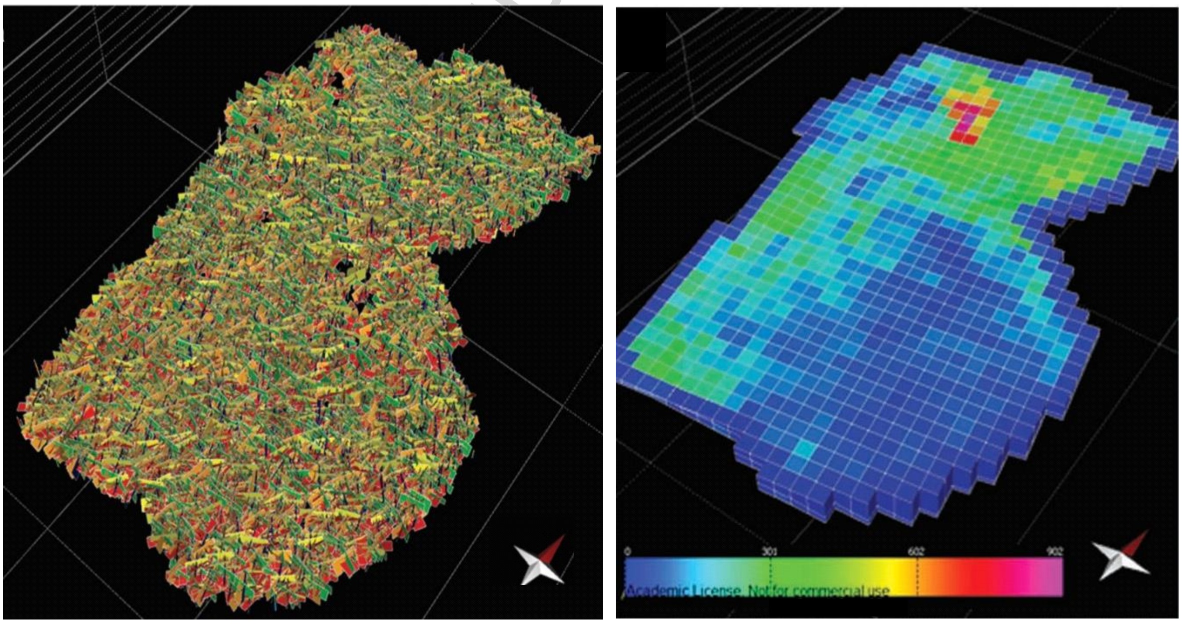


Figure 6- Fracture model and associated permeability map for Higher Moor pit. The DFN (left figure) calculated for Higher Moor pit contains intersections of five discontinuity sets (density = 50%) while the permeability map (right figure) is assessed by connectivity analysis. The high permeability values (red) in the central northern section indicate where fluid accumulation and flow would have been greatest, implying that kaolinisation will have progressed to an advanced level in this area.

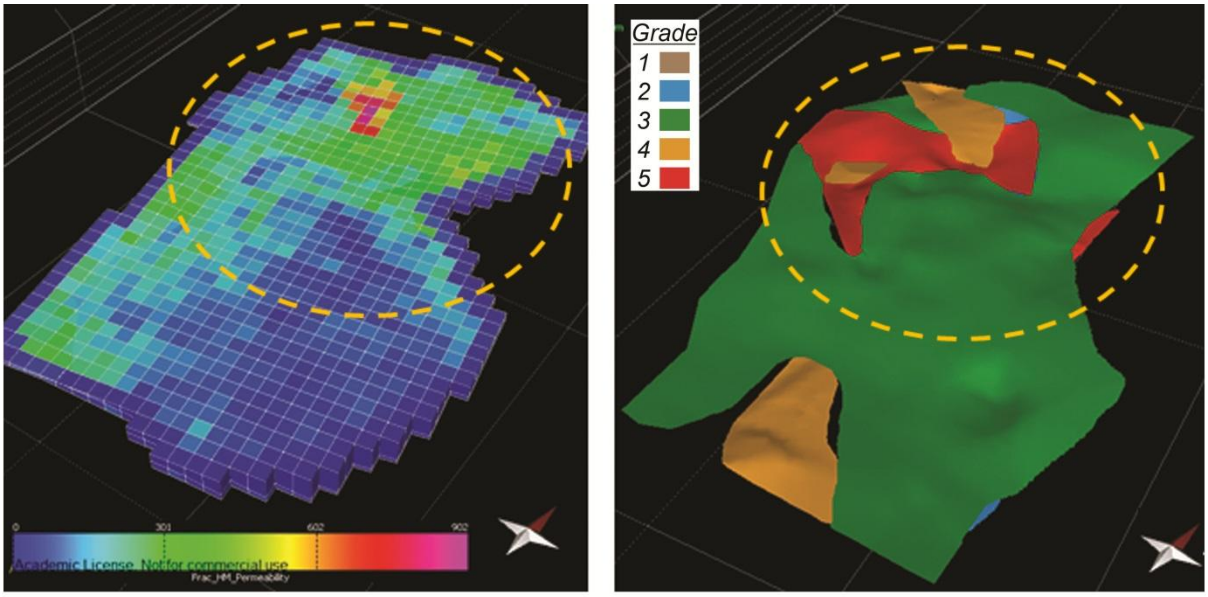


Figure 7- Comparison of DFN (left) and deposit model (right). Superimposing a dashed circle around the highly permeable section indicates the zone of high-grade alteration at the case study site.

Tables

	Dip	***Azimuth***	***Fisher (k)***
Set 1	85	179	79.1
Set 2	45	181	51.7
Set 3	81	220	25.6
Set 4	88	283	43.9
Set 5	84	138	63.1

Table 1- Summary of major discontinuity sets and their associated Fisher (k) values.

Fault	***Mode***	***Strike/Dip***	***Orientation***
Field Measurement	Extensional Simple Shear	052/85	ENE/WSW
Field Measurement		160/87	NNW/SSE
Model-Based		173/85	NNW/SSE

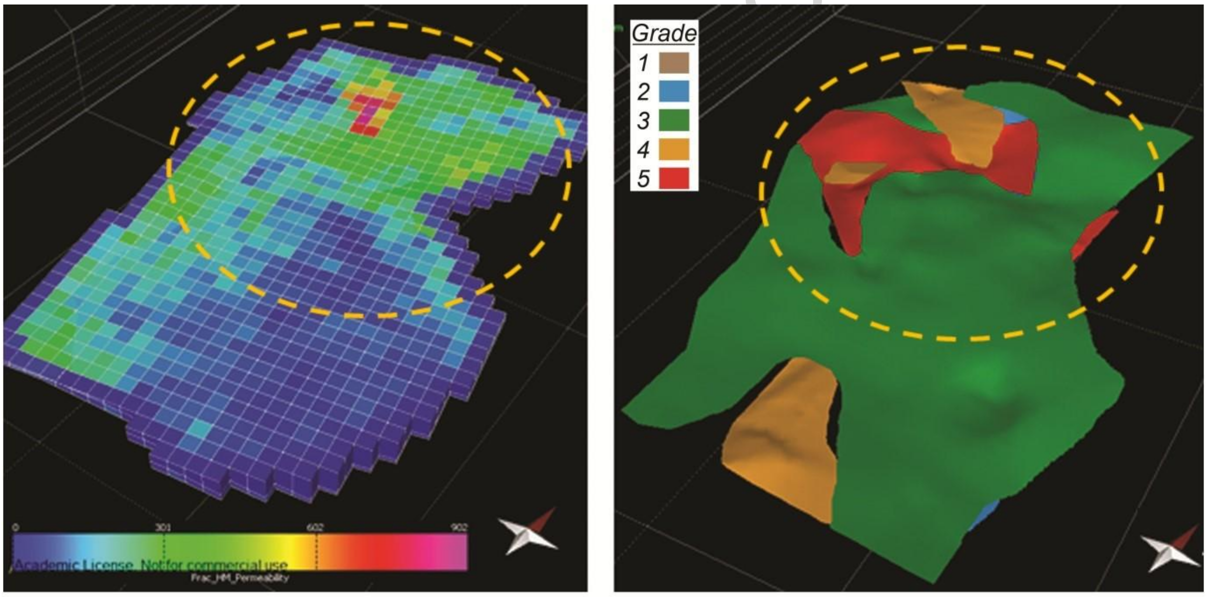
Table 2- Summary of orientation, dip and movement for Higher Moor faults used during simulation. This information served to model the deposit in four-dimensions and estimate strain data.

Parameter	***Set According To***
Intensity	P32; e1/e3
Length	Random

Aspect Ratio	1:2
Aperture	Proportional to root length

Table 3- Parameters used during DFN analysis for fracture sets.

Graphical Abstract (Figure 7)



Highlights

- The relationship between kaolinisation and structural features is defined
- The chosen study location is described and measurements demonstrated
- A discrete fracture network is modelled to locate zones of high fluid circulation
- Zones of high permeability match well with zones of advanced kaolinisation