

In-situ study of texture-breakage coupling in a copper ore using X-ray micro-CT

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ABSTRACT

As the mining industry continues to seek greater energy efficiency, it needs more effective characterization of ore material as it progresses from mine to mill. The energy cost of ore mineral liberation, for example, is critically dependent on management of rock breakage from blasting to comminution. The study reported here presents a quantitative method for 3D characterization of ore texture and breakage based on X-ray micro-CT and in-situ micromechanical test. A porphyry copper ore is studied from its initial mechanical failure to the onset of fragmentation. This work integrates a quantitative ore textural analysis with 3D mapping of both the dominant minerals and micro-porosity in the ore sample. It enables us to show, as the fractured ore is still under loading, that internal breakage of feldspar grains dominates grain boundary fracturing. We discuss how the microporous regions, mostly found in hydrothermally altered plagioclase, may act as a weakening factor leading to the dominant breakage of plagioclase. We measure quantitatively and discuss how size reduction, ore texture and breakage characteristics control the degree of liberation of Cu minerals. Combining characterisation of ore texture with breakage in 3D could provide much needed insights for achieving more energy-efficient comminution and optimal liberation of critical minerals.

1. Introduction

Porphyry copper ores are composed of multiple mineral phases including target minerals (e.g., chalcopyrite, bornite) and gangue (e.g., feldspars, quartz). The target minerals only account for a tiny volumetric fraction of whole rock mass and are embedded in and between other minerals. In order to be recovered, the valuable target minerals must be liberated from the gangue. This comminution process (Ballantyne and Powell, 2014; Wills et al., 2016) involves crushing and grinding to reduce fragment size. This ore breakage process is energy intensive (Ballantyne and Powell, 2014) and also determines the efficiency of mineral recovery in downstream processes, e.g., froth flotation and leaching (Wills et al., 2005; Wills et al., 2016; Sinclair and Thompson, 2015; Petersen, 2016). Energy-efficient comminution and maximal mineral extraction are key to the economics of copper mining.

In order to mitigate the energy costs of comminution, improved

understanding of the breakage behaviour of copper ores is needed. Two types of breakage are commonly defined based on where they occur: random versus preferential breakage (Semsari Parapari et al., 2020; Mariano et al., 2016). For random breakage, the resulting fracture patterns are independent of the mineralogical composition and texture of the rock (King and Schneider, 1998). Preferential breakage has biases for a mineral phase or grain boundaries. Better understanding on whether a certain type of mineral undergoes random or preferential breaking will help building more robust models that could predict mineral liberation in a comminution process (King and Schneider, 1998; Gay, 2004; Gay, 2004). Therefore, previous studies have focused on separating and quantifying these two types of breaking. For instance, based on X-ray micro-CT, Garcia et al. (Garcia et al., 2009) quantified grain boundary fracturing of sulfide copper ore samples by tracking the changes in the interfacial area between target minerals and gangue. This work demonstrated the potential of 3D X-ray micro-CT in this field but it only focused on the breakage associated with the target minerals and the

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Nomenclature

φ	voxel porosity
I	grayscale value
S	interfacial area between phases

behaviour of other minerals was not analysed. It would obviously be interesting to use micro-CT to produce a complete 3D description of the breakage behaviour of multi-phase ores.

In the context of mineral beneficiation, the breakage behaviour of ores has to be discussed with respect to ore texture heterogeneity, which may include multiple factors such as mineralogy, grain size and geometry, mineral spatial distribution and contact type/relationship (Lund et al., 2015; Gaspar and Pinto, 1991; Parian et al., 2018; Bonifazi et al., 1990). Ore texture analysis is becoming a popular method for studying the breakage of heterogeneous ores and mineral liberation (Semsari Parapari et al., 2020; Gaspar and Pinto, 1991; Parian et al., 2018; Guntoro et al., 2021). Such analyses usually rely on various imaging techniques and image processing methods to extract textural information of rocks (Wang, 2015; Vizcarra et al., 2010). Ideally, quantitative textural descriptors would not only be able to classify ores but also could be helpful for predicting their breakage behaviours (Bonnici et al., 2008; Guntoro et al., 2020). To achieve this, significant effort has been made to link ore texture and breakage, which mostly used two-dimensional image-based methods. For instance, Vizcarra et al. (Vizcarra et al., 2010) used specific interfacial area (SPIA) as a textural indicator to distinguish different breakage types. Parian et al. (Parian et al., 2018) developed the Association Indicator Matrix (AIM) method aiming to quantify the frequencies of random and preferential breaking for each specific ore texture. One advantage of this method is that it provided quantitative ore characterization in terms of phase association. However, the ability of association indicators to define breakage types needs to be improved, as different breakage behaviours may have the same association indicator. Refined methods that unambiguously characterise different breakage types are needed.

In addition to ore texture, discontinuities such as pre-existing cracks and porosity may also affect the breakage behaviour of ores (Mahabadi et al., 2014; Griffiths et al., 2017; Liu et al., 2022; Germanovich et al., 1994). While there is a body of literature on pre-existing cracks and their effect on the mechanical properties of rocks, e.g., as reviewed by Liu et al. (Liu et al., 2022), how porosity (at sub-micrometer scale, in particular) affects the breakage of a rock was rarely reported. Porosity in copper ores is typically at sub-micrometer scale (Henley et al., 2022). It can be measured by using advanced instruments such as scanning electron microscope (SEM), however this can only be achieved on relatively small samples. Using high X-ray attenuating contrast agent such measurements can be performed on larger samples. For instance Zhang et al. (Zhang et al., 2021) have successfully mapped the 3D distribution of micro-porosity for a highly heterogeneous copper ore sample using CH_2I_2 . More research is needed to explore the potential of this method in particular to study the impact of micro-porosity on ore

breakage behaviour.

In this study, we aim to introduce a new X-ray micro-CT-based methodology that enables us to characterise porosity-breakage coupling for the dominant minerals and mineral assemblages in a copper ore. Using this method, we investigate the breakage behaviour of a porphyry copper ore sample. We employ 3D X-ray micro-CT and in-situ micromechanical testing to acquire and reconstruct a sequence of 3D images of a copper ore on a quasi-static path to the onset of fragmentation. Discontinuities in the sample, which are mostly sub-micrometer and will be referred to as micro-porosity hereafter, are mapped in 3D and studied in relation to the breakage behaviour. A new texture analysis method based on phase interfacial area is used to separate and quantify different breakage types. The size of the resulting fragments is measured from images and analysed in relation to the breakage and mineral liberation process.

2. Materials and methods

2.1. Sample preparation and 3D mapping of micro-porosity

The core sample studied is a copper ore, more precisely a volcanoclastic breccia that contains clasts of porphyritic andesitic volcanic lava and volcanic sediments. For this study, a 12 mm diameter 40 mm length core was used (Fig. 1), which was taken from a 45 mm diameter NQ3 drill core.

All CT images were acquired at the National Laboratory for X-ray Micro Computed Tomography (CTLab) at the ANU. The typical pore size of such rocks is below the highest spatial resolution ($\sim 1 \mu\text{m}$) of laboratory-based X-ray micro-CT scanners. To measure this micro-porosity, the authors have developed a methodology based on a contrasting agent which enables the 3D mapping of connected sub-resolution micro-pores on a per voxel basis without directly resolving the pores (Fogden et al., 2014; Zhang et al., 2017; Zhang et al., 2019; Zhang et al., 2019; Zhang et al., 2018; Zhang et al., 2023). To map the micro-porosity, two scans of the sample were acquired, one with the sample in its original ("dry") state and one in a "wet" state after saturation with a contrast agent (i.e. diiodomethane CH_2I_2). Both scans were acquired at $4.3 \mu\text{m}/\text{voxel}$ to ensure optimal image quality. CH_2I_2 is a highly X-ray attenuating fluid and here it was used for highlighting the connected micro-porosity. In the wet tomogram porous regions of the sample will significantly attenuate the X-ray flux compared with the dry due to the saturation of CH_2I_2 . The attenuation map of the dry image is then subtracted from that of the wet image to obtain a difference map. In the latter, more porous regions will have a greater attenuation difference. Local (or voxel) porosity can then be quantified from the attenuation difference of a voxel which reflects the degree of porosity. Equation 1 was used to calculate the micro-porosity of each voxel using the dry and wet tomograms.

$$\varphi_{(x,y,z)} = \frac{I_{(x,y,z)}^{\text{wet}} - I_{(x,y,z)}^{\text{dry}}}{I_{\text{CH}_2\text{I}_2}} \quad \text{Equation 1.}$$

where:

- $\varphi_{(x,y,z)}$ is the voxel porosity at location (x,y,z) in the tomogram.

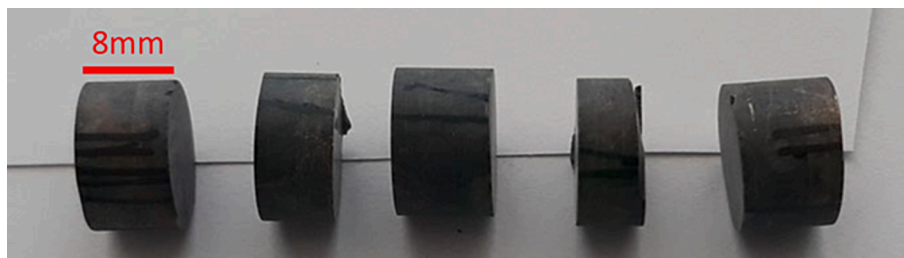


Fig. 1. Picture of the copper ore sample after cutting into sub-samples.

- $I_{(x,y,z)}^{dry}$ and $I_{(x,y,z)}^{wet}$ are the grayscale values at location (x,y,z) in dry and wet tomogram, respectively.
- I_{CH2I2} is a constant value and it is equal to the net increase in grayscale value of a fully resolved pore with 100% CH₂I₂ saturation in the wet tomogram.

After mapping the micro-porosity in 3D, the 40 mm long sample was cleaned by circulating toluene through the pore spaces. The cleaned sample was naturally dried under ambient conditions and cut into 8 mm long sub-samples (Fig. 1), one of this which was chosen for the in-situ mechanical testing.

On a side note, another 7 sister cores (12 mm diameter 8 mm length) extracted from the same 45 mm diameter NQ3 drill core were tested. Four of these cores were directly tested in-situ, while the three others were first saturated with the contrasting agent to estimate their micro-porosity before being cleaned and mechanically tested. There was no noticeable weakening effect on the mechanical behaviour of these three cores due to the impregnation with the contrasting agent. The force at onset of fragmentation for these cores was in the range [6.3 – 8.3] kN.

2.2. Fragmentation experiments

The in-situ micro-mechanical experiment is based on a high-pressure triaxial flow cell (the XCT-HP apparatus, Fig. 2) which is fully integrated to an advanced micro-CT scanner equipped with a laboratory X-ray source. Over the past 15 years, the development of the XCT-HP apparatus at the ANU has been guided by different research activities in

model granular materials (Francois et al., 2013; Saadatfar et al., 2012; Hanifpour et al., 2014; Saadatfar et al., 2017), in engineering materials (Francois et al., 2008) and more recently in problems related to CO₂ geological storage (Øren et al., 2019; Huang et al., 2023; Herring et al., 2021). More details on this instrumental platform can be found in (Francois et al., 2022). To perform a tensile activated fragmentation test, we used an in-house designed crushing device. This crusher module is shown in Fig. 2 (c). It is composed of a pair of curved aluminium jaws encapsulated in a cylindrical jacket made of polyetheretherketone (PEEK). This module sits in the confining chamber of the high-pressure apparatus. A disc-shaped ore sample (diameter $d = 12$ mm, thickness $t = 8$ mm) is placed in the crusher. As the ore is compressed between the two jaws, a compressive stress is directed along the diameter of the rock while tensile stresses develop in the horizontal direction. Loading is provided by a hydraulic syringe pump (MetaRock Laboratories, Houston, USA) that is connected to a PID controller that enables an accurate and optimal control of the axial force F applied to the lower jaw. Ten high-resolution 3D images were acquired at different stages of the mechanical test, and the loading condition at each stage is given in Table 1. For acquiring high quality images with good contrast between minerals, long scans were undertaken (~17 h per image), with a spatial resolution (i.e. the voxel size) of 9 μ m. The X-ray source operated at 100 Kev with a 0.25 mm-thick aluminium filter.

The protocol between each loading stage consists of:

- 1) a pressure ramp at a rate of 6.8×10^{-4} MPa/s, until a set loading value was reached;

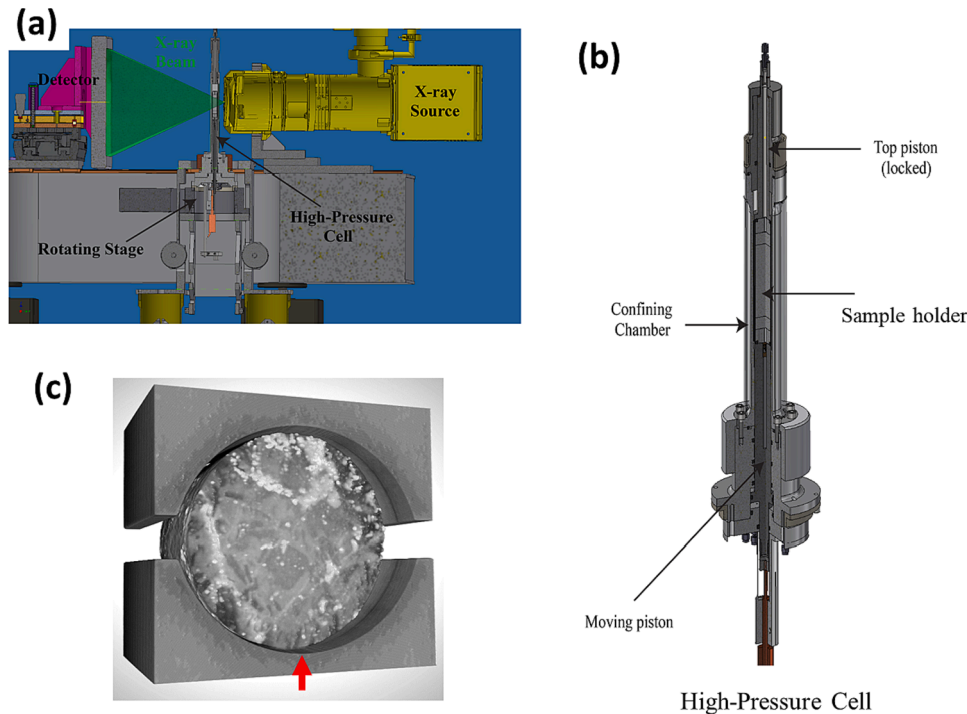


Fig. 2. Schematics of the rock fragmentation apparatus with in-situ imaging system. (a) shows the main configuration of the system; (b) is the high-pressure cell where the sample is fragmented; (c) shows the sample sitting between two jaws in the sample holder; red arrow indicates the moving direction of the lower jaw. The upper jaw is locked. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Load steps in the fragmentation test.

Load step #	1	2	3	4	5	6	7	8	9	10
Image name	P100	P175	P250	P325	P400	P500	P600	P700	P800	P1030
Load on the piston (psi)	100	175	250	325	400	500	600	700	800	1030
Force on the rock sample (kN)	0.75	1.3	1.82	2.4	2.92	3.67	4.4	5.12	5.9	7.5

- 2) a 4 h-long conditioning period, during which the axial displacement was fixed (e.g., constant strain) and the axial pressure relaxed to some extent (Francois et al., 2022);
- 3) image acquisition at fixed strain of the sample to minimise sample movement during scanning.

As shown in (Francois et al., 2022), the measurement of the stress relaxation allowed us to measure a relaxation time of the rock for each loading stage. In this experiment, this relaxation time was typically of the order of 4 h. It seemed to correspond to the collective relaxation of the fracture network. Each image was acquired after a 4 h-long relaxation period. In that sense, we argue that the sequence of images allowed quasi-static tracking of the breakage of the rock.

2.3. Image processing

Two image processing steps, i.e., image segmentation (Schlüter et al., 2014) and particle separation (or labelling) (Zheng and Hryciw, 2016) underpin the new image-based breakage characterisation method, which will be introduced in the next section. Image segmentation was used to classify image voxels into different phases according to their grayscale values. To ensure quality image segmentation, an anisotropic diffusion filter was used to denoise the images. Then, an unsharp mask filter was used to enhance phase edges. Then image segmentation was done using a converging active contour method, which is a combination of the watershed and active contour methods (Sheppard et al., 2004). Phases in segmented images were linked to different mineral groups, which was guided by applying Quantitative Evaluation of Materials by Scanning Electron Microscopy (TMQEMSCAN) on polished thin sections of the sample. Segmented images were also used to calculate phase interfacial areas in 3D, which is part of the textural analyses of the sample. The method for calculating interfacial area from images is described in (Ohser and Mücklich, 2001). Particle separation is to separate touching fragments (broken pieces of the sample after crushing) from an image and give each fragment a unique label (Fig. 3). This is

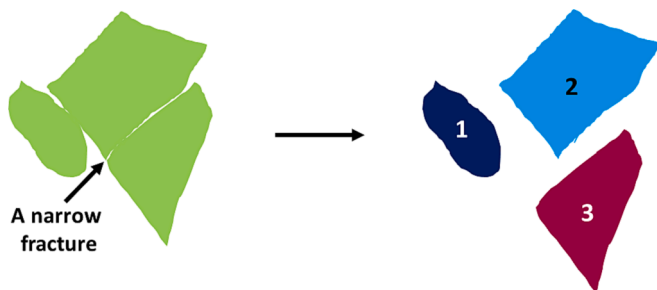


Fig. 3. A schematic illustration of particle separation. The narrow fracture indicates a sub-resolution fracture that is visible to human's eyes but may not be identified accurately in segmentation. This may affect particle separation.

a necessary step before total fragment number and individual fragment size can be quantified because otherwise all the fragments will be in contact with others and form a connected object in an image. The method for particle separation is a watershed transform-based method and more explanation can be found in (Zheng and Hryciw, 2016) where a similar 2D method was used. More examples of particle separation and counting from images can be found in (Zhang et al., 2021; Jiang et al., 2021). It is important to note that the particle separation process was quite challenging for the in-situ images acquired in this work. This is because fractures between fragments, which are important to define fragments boundaries, could fall below the resolution of the images, as illustrated in Fig. 3. As a result, fragments that are tightly touching and have a large contact area (e.g., particle #2 and #3 in Fig. 3 before separation) might not be separated accurately. This issue was partially mitigated by using a high image resolution and carefully segmenting as many fractures as possible. For segmenting those small cracks, e.g., below 1–2 voxels in aperture, it is best to use a contrast agent (Zhang et al., 2021) during imaging, which could be adopted into this workflow in future experiments. 3D image registration (or alignment) was used on the dry & wet image pair to facilitate a voxel-voxel subtraction between them. All image processing work was carried out using an in-house software package, MANGO (Sheppard et al., 2004). The 3D volume rendering for this paper was generated using Dragonfly software, developed by Object Research Systems (ORS) Inc, Montreal, Canada.

2.4. Breakage type characterization

Breakage characterization was undertaken both qualitatively and quantitatively. Fracture patterns were first visually examined in 3D to look for evidence that they were affected by micro-porosity and/or any mineral phase. This was done by combining information from the micro-porosity mapping, segmentations and TMQEMSCAN images. Then breakage patterns within the whole sample were quantitatively characterized using 3D ore texture analysis as follows. For a mineral of interest (e.g., phase A in Fig. 4) in a multi-phase rock, two basic types of breakage are defined: Type I, along its interface with other minerals; and Type II, inside itself without breaking any mineral interface. Based on these two basic types, a hybrid type could also occur, which is a combination of Type I and II. All these breakages lead to an increased contact with air (shown by shaded areas in Fig. 4) for phase A. If air, which is a result of fracturing, is considered as the fourth phase, each of these breakage behaviours leads to a change of rock texture. For instance, after breakage Type I all the three minerals (A, B and C) have a direct contact with air and phase A is no longer in contact with B or C; and after breakage Type II, only mineral A has a direct contact with air and the contact relationship between B and C remains unchanged. Rock texture analysis before and after breakage has become a popular method for studying the breakage of rocks. For instance, the Association Indicator Matrix (AIM) method (Parian et al., 2018) is a recent approach for texture analysis. This approach has some predictive power; however,

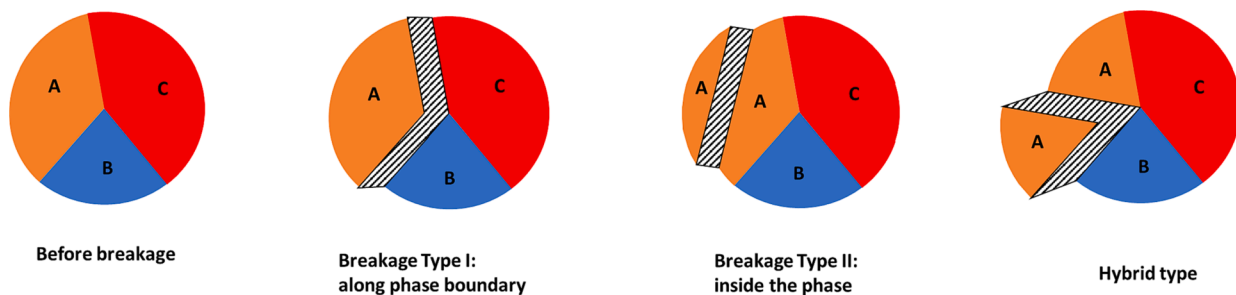


Fig. 4. Schematics showing 2 basic breakage types for target mineral A in a rock containing 3 minerals (A, B and C) and a hybrid type which is a combination of the two basic types. Shaded areas indicate air (void space) after fracturing. Assume that the original perimeter of the rock is not in contact with air and air only exists after breakage occurs.

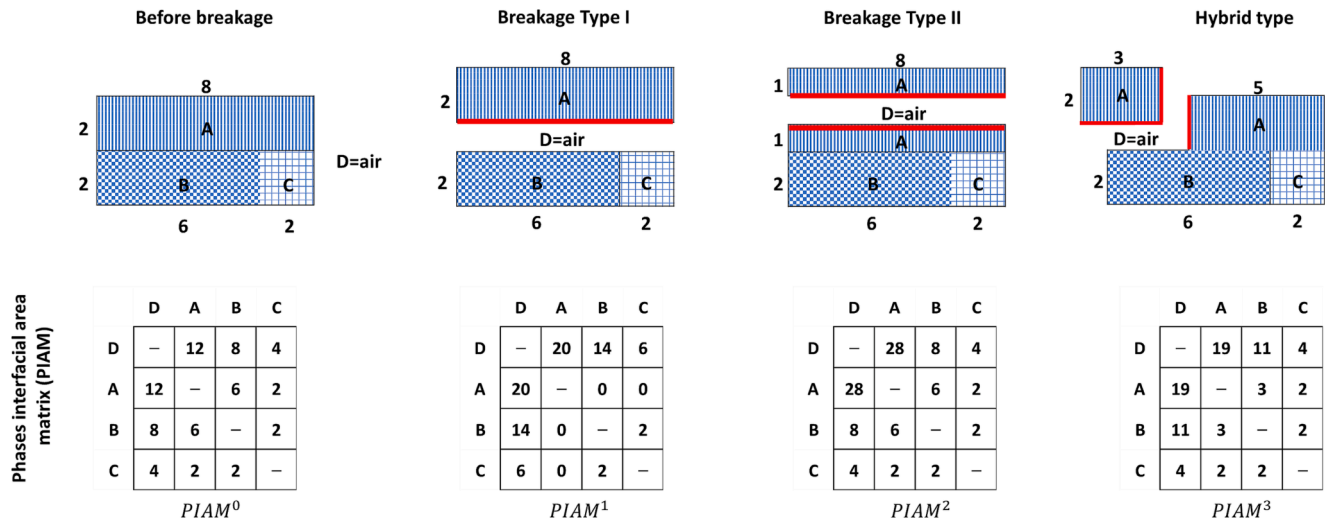


Fig. 5. An intact rock model and 3 different breakage scenarios, and their corresponding phase interfacial area matrices (PIAM). The matrices are designed to quantify the interfacial area between pairs of different phases, so the entries of the main diagonal for each matrix are undefined. Red lines indicate increased exposure of the target phase A after breakage. Note that for this simple case, interfacial area between a pair of phases was simply calculated by the total length of contact lines between the two phases. It is also assumed here that the original perimeter of the rock is in direct contact with air. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

one important drawback of the AIM method is its inability to distinguish certain breakage behaviours. Different contact relationships between two phases may have the same association indicator. More explanations can be found in the [Supplementary Materials](#).

To overcome the limitations of the AIM method, a modified method is used in this study. This method is also based on texture analysis but uses 3D interfacial area between phases (denoted by S) as the descriptor for texture. In this method, contact relationships (expressed as a phase interfacial area matrix, PIAM) between phases are tracked before and after breakage. This new method identifies breakage types by quantifying how a given phase increases its exposure to air. For breakage Type I, phase A's increase of exposure to air is 100% from the loss of its interfacial area with B (i.e., S_{A-B}) and C (i.e., S_{A-C}). For breakage Type II, phase A's increase of exposure to air is 100% from internal fracturing of A with no loss of interfacial area. For the hybrid type, it is a mix of Type I and II.

A simple 2D application of a PIAM is illustrated in Fig. 5 which, shows the same breakage scenarios as in Fig. 4 but in a quantitative way. The 2D rock model ("before breakage"), with a size of 8 by 4 pixels, has 3 phases (A, B and C) and is surrounded by phase D, the air phase. From $PIAM^0$ to $PIAM^1$, S_{A-D} increases from 12 to 20, which is a net increase of 8; at the same time, both S_{A-B} and S_{A-C} become 0, which indicates a loss of interfacial area of 8. A comparison between $PIAM^1$ and $PIAM^0$ indicates that phase A is entirely broken from the original rock and its increased interfacial area with air is purely a result of losing contact with B and C, which is exactly what breakage Type I shows. By comparing $PIAM^2$ and $PIAM^0$ it is observed that both S_{A-B} and S_{A-C} remain unchanged while S_{A-D} increases from 12 to 28. This indicates that increased interfacial area with air for A is purely from internal breakage of A and no phase interface is broken, which is breakage Type II. This new method also works well for the hybrid breakage type and can quantify the relative frequencies of the two basic types. From $PIAM^0$ to $PIAM^3$, S_{A-B} decreases from 6 to 3 and S_{A-C} keep unchanged, which indicates that some Type I breakage occurs along A-B phase boundary but not A-C phase boundary. The Type I breakage along A-B phase boundary gives A an increase of S_{A-D} by 3 (i.e., 6 minus 3). However, the total increase of S_{A-D} is 7 (from 12 to 19), which suggests that A must also have some Type II breakage that increases S_{A-D} by 4 (i.e., 7 minus 3). So, one could infer that phase A experiences the hybrid breakage type; and 43% (i.e., 3/7) of the increased S_{A-D} is from Type I and 57% (i.e., 4/7) is from Type II. Liberation (here defined as the ratio between exposed surface area

with air and total surface area, i.e., surface exposure) of each phase can also be derived from its contact relationships. For instance, in $PIAM^1$ phase A has 100% liberation (20/20) and in $PIAM^2$ it has 78% liberation (28/36).

3. Results and discussions

3.1. Micro-porosity and mineralogy

The micro-porosity mapping for the porphyry copper ore sample is illustrated in Fig. 6, for 2 cross-sections through the tomogram, one from the top of the sample (upper row) and one from the bottom (lower row). The corresponding dry and wet tomogram slices are also shown. Subtracting the dry from the wet tomogram gives the micro-porosity map, which highlights the micro-porosity areas (by blue-to-red colors) and leaves all non-porous areas as blank background. From these two cross-sections, three types of micro-porosity may be observed: 1, within some disseminated mineral grains (e.g., red ovals in Fig. 6); 2, along narrow bands (e.g., black oval in Fig. 6) and 3, within some minerals that seem denser than those in type 1 (e.g., purple oval in Fig. 6). Comparing the micro-porosity map with the dry tomogram, it can be seen that the porous narrow bands coincide with the veins. The mineralogy of the micro-porous grains will be investigated in later part of this section with the aid of TMQEMSCAN results.

Based on the voxel porosity calculated from Eq. 1, the total estimated porosity of the full 40 mm-long sample is between 0.18% and 0.67%. This range of values is a result considering the uncertainties in determining a cut-off grayscale value for micro-porosity. The lower micro-porosity corresponds to a higher cut-off value where weak signals (numerator of Eq. 1 < 1000) were considered as noise; the higher one corresponds to a lower cut-off value where most signals were considered as micro-porosity. Based on a total porosity of 0.42%, which is a middle case scenario, the micro-porosity distributions across two longitudinal slices of the sample are shown in Fig. 7. The total porosity per cross-sections from top to bottom of the sample is also calculated and shown. It shows obvious variations in micro-porosity in the axial direction of the sample. Micro-porosity at the very top section can be as high as 2% while it drops to very low values in the middle of the sample. Micro-porosity in the very top section is mainly type 3 whereas type 1 is mainly in the lower 1/3 of the sample, where the subset for fragmentation was taken. Type 2, which forms microporous bands that are

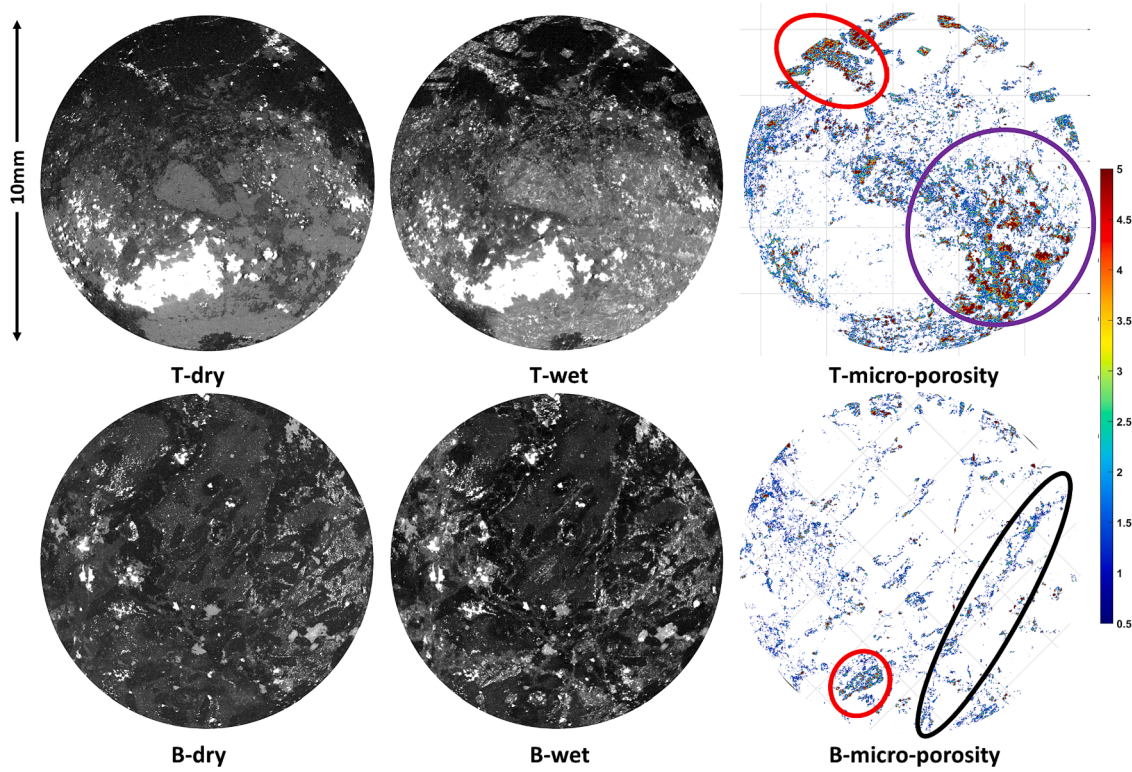


Fig. 6. Cross-sectional image slices (XY slices) of the sample, showing the dry and wet tomogram slices and the micro-porosity maps. Upper row is taken from the top of the sample and lower row is from the bottom of the sample. The micro-porosity maps highlight the micro-porous region only, showing higher micro-porosities by red colors. The red ovals show examples of disseminated micro-porous grains. The blue oval shows an example of long narrow porous band. The purple oval shows a broader microporous area and the minerals seem denser (brighter in the dry image) than those indicated by red ovals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

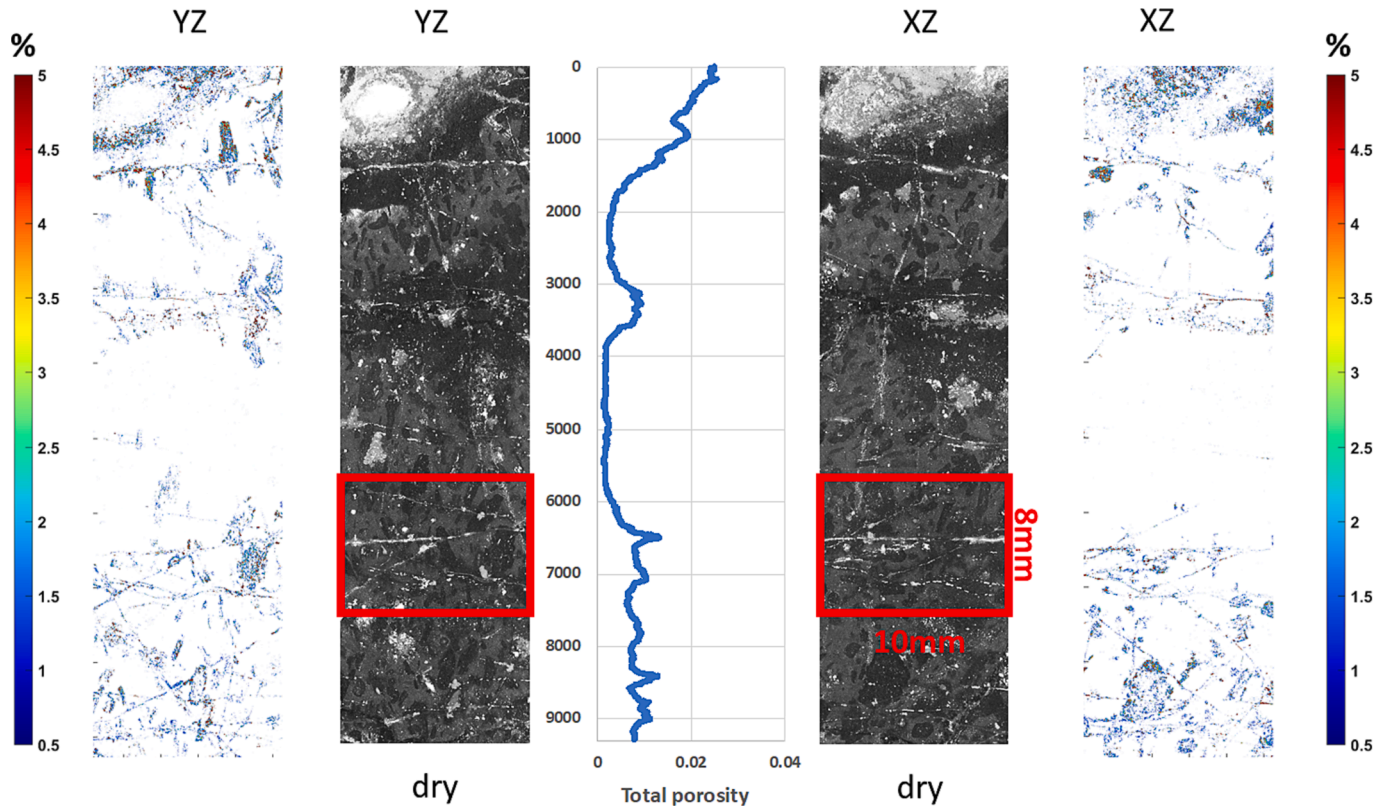


Fig. 7. Micro-porosity distribution in two longitudinal slices (YZ and XZ slices) of the full sample, together with images from the dry tomograms. Plot in the middle shows the total micro-porosity per cross-sectional slice of the sample, from top to bottom, in fraction. Red frames indicate the location of the sub-sample used in the fragmentation test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

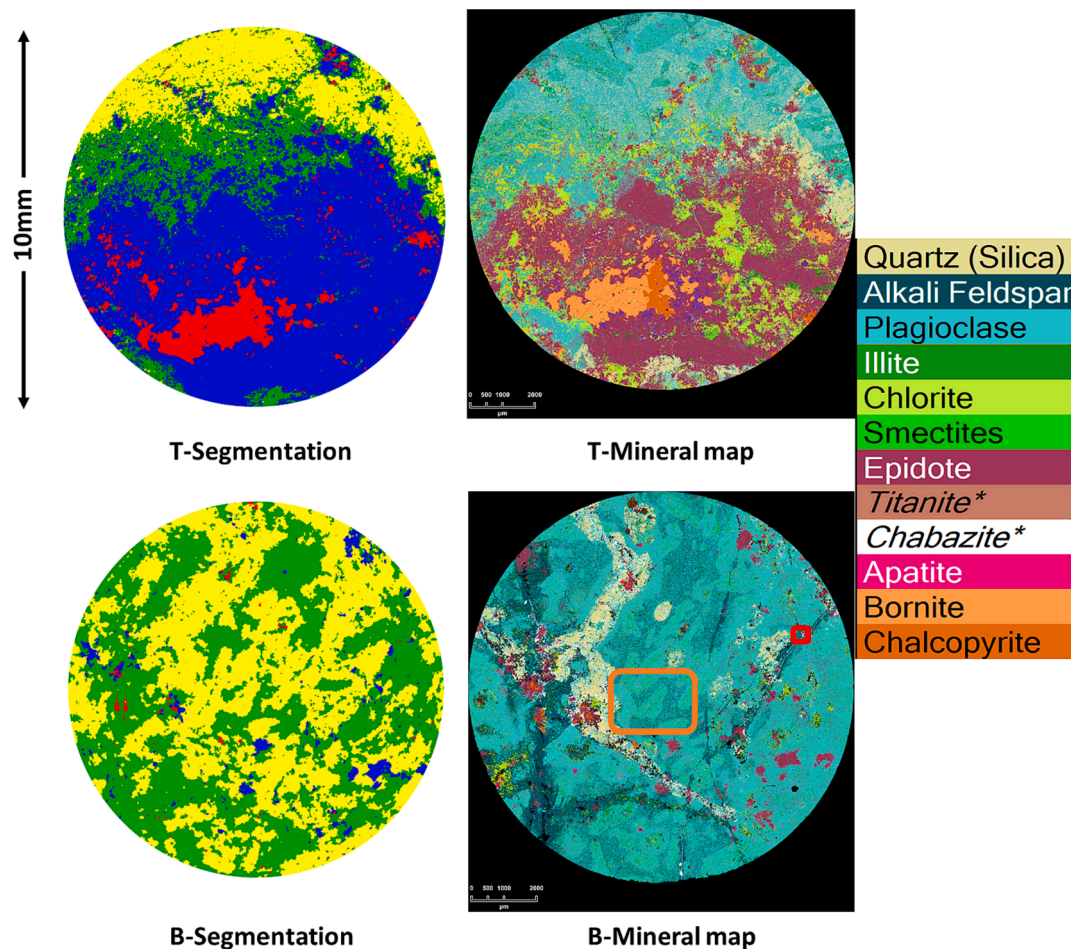


Fig. 8. Phase segmentation and mineral analysis of two cross-sectional slices. Upper row was taken from the top of the 40 mm-long sample and lower from the bottom of the sample. In the segmentations, yellow phase mainly includes plagioclase and quartz; green phase mainly includes alkali feldspar; blue phase is mainly epidote and minerals associated with veins; and red phase is copper sulfides (bornite and chalcopyrite). High resolution SEM images of the areas in orange and red frames in “B-mineral map” are shown in Fig. 10. The legend of the TMQEMSCAN mineral map only lists the principal mineral phases. Pixel size of the TMQEMSCAN mineral maps is $\sim 20 \mu\text{m}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

associated with veins, traverses the sample. It should be noted that our method only captures the connected micro-porosity. So, it is possible that the middle section of the sample has some level of non-connected micro-porosity that was not captured.

Two polished thin sections of the sample were analysed by TMQEMSCAN and they correspond to the slices shown in Fig. 6. TMQEMSCAN images (Fig. 8) suggest that the sample was mainly composed of quartz, feldspars (alkali feldspar and plagioclase), clays and epidote; and the copper-containing minerals were bornite and chalcopyrite. The different grey levels in a tomographic image reflect X-ray attenuation variations through the constituents of the scanned material. Using cross referencing between a tomogram section and its corresponding TMQEMSCAN map enable us to establish the relationship between a range of grey-levels and a given mineral in the 3D core volume. Segmentation and classification of the two tomogram slices is shown in Fig. 8. On a technical note, only 4 phases were segmented from the tomogram, which is mainly due to the fact that some minerals have similar X-ray attenuation properties. In the segmentation images in Fig. 8, the yellow phase is mainly plagioclase, quartz and others; the green phase is mainly alkali feldspar; the blue phase is mainly epidote

and minerals associated with veins; and the red phase is the copper sulfides. Note that, as suggested by “B-mineral map” of Fig. 8, plagioclase and quartz present as large distinct grains although they were both included in the yellow phase.

Image segmentation results of the full 40 mm sample are shown in Fig. 9. The phase volume fractions computed on the 3D volume of the full sample are given in Table 2. It shows that the yellow phase (plagioclase, quartz, etc.) and the green phase (mainly alkali feldspar) have similar phase volume fractions, which are around 40%. Blue phase (mainly epidote and minerals associated with veins) is 12% and mainly occurs at the top section. Copper minerals are only 1.5% of the total volume. 3D micro-porosity mapping was registered to the 3D segmentation (Fig. 9), so micro-porosity of each phase was also calculated and shown in Table 2. The yellow phase has 40% of the total micro-porosity. Since quartz is non-porous, micro-porosity of the yellow phase is mainly from plagioclase. The blue phase has a similar micro-porosity as the yellow phase, which is 36% of the total. However, it is worth noting that both microporous veins and epidote were included in the blue phase during segmentation. So, the actual micro-porosity of epidote alone should be lower. Since blue phase is mainly at the very top of the sample,

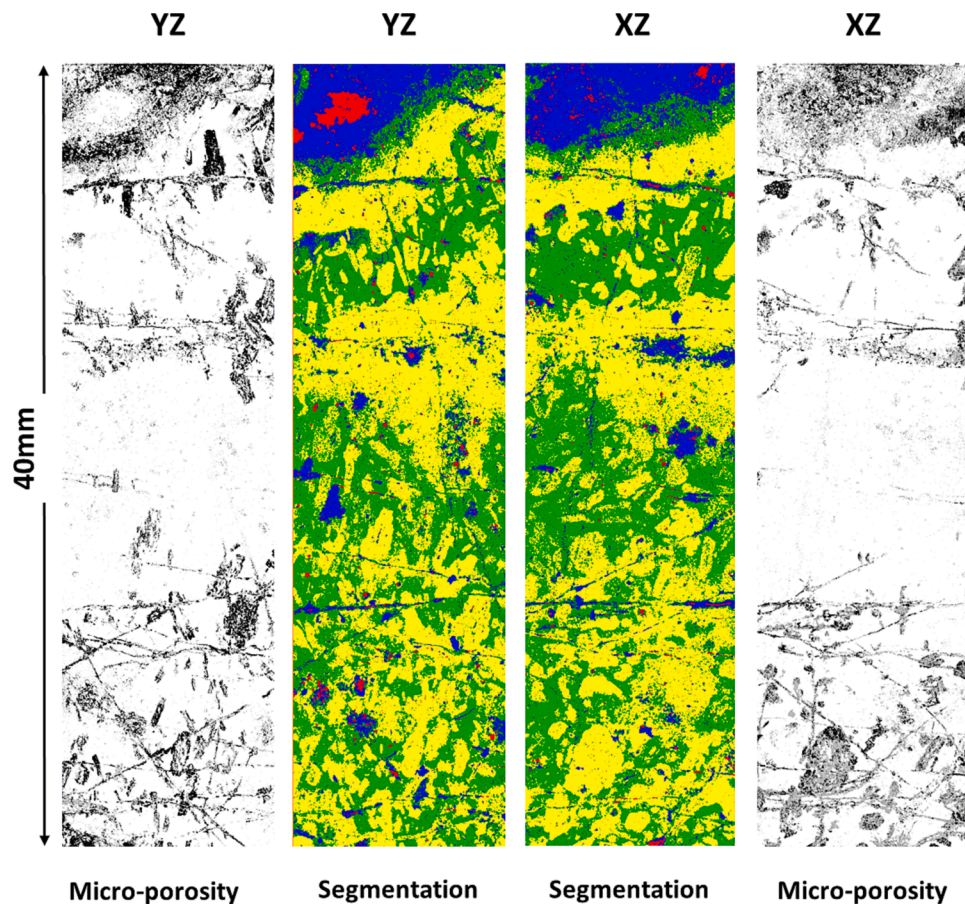


Fig. 9. Vertical slices taken from 3D segmentation result of the whole sample, comparing with the corresponding micro-porosity maps. In segmentations, yellow phase mainly includes plagioclase and quartz; green phase mainly includes alkali feldspar; blue phase is mainly epidote and minerals associated with veins; and red phase is copper sulfides. In micro-porosity maps, black indicates micro-porosity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Phase volume fractions (%) from segmentation for the whole sample. Phase porosity fraction is the ratio between porosity of a phase and total porosity of the whole sample. Only the main minerals included in each phase are listed. More information can be found in the Supplementary document.

	Yellow (Plagioclase, quartz)	Green (Alkali feldspar)	Blue (Epidote and minerals associated with veins)	Red (Copper sulfides)
Phase volume fraction - %	46	41	12	1.5
Phase porosity fraction - %	40	22	36	2

it is reasonable to conclude that plagioclase and veins are the largest source of micro-porosity for the rest of the sample.

High resolution SEM images taken from one of the polished thin sections (at locations indicated by the orange and red rectangles in the TMQEMSCAN mineral map in Fig. 8) are shown in Fig. 10. Inset (a), corresponding to the orange rectangle, mainly shows some plagioclase grains. The corresponding micro-porosity map is inset (b). A smaller region of a plagioclase grain is further enlarged to show the pore space, see inset (c). It can be seen that micro-pores are abundant; they have irregular shapes and form clusters. The micro-porosity might be a result of chemical reaction (Henley and Fischer, 2021; Henley and Berger, 2013) between reactive magmatic gas flow and the rock, which replaced reactive minerals such as calcic plagioclase feldspar by potassic feldspar accompanied by development of porosity (Henley et al., 2022). Inset (d), which corresponds to the red rectangle in the TMQEMSCAN mineral map of Fig. 8, shows the mineralogy and micro-porosity associated with a vein. It is observed that the vein is filled with calcite and chabazite and traverses the rock mass that contains alkali feldspar (K- and Na-

feldspar). Micro-cracks in the chabazite were probably formed subsequent to deposition due to dehydration. These veins formed during the retrograde stage of the development of the deposit and are unrelated to the pervasive feldspar alteration described above and which is directly related to the process of sulphide mineralisation. How these late porous veins and *syn*-mineralisation altered plagioclase grains affect the breakage behaviour of the rock sample will be discussed in next section.

3.2. Mechanical failure and onset of fragmentation

3.2.1. Overview of the fragmentation test

Fig. 11 shows the force-strain relation measured during the 15-day-long experiment. Loading condition at each step is given in Table 1. The strain ϵ is computed as $\epsilon = \delta l / d$ where δl is the change in the gap distance between the jaws. The 4 in-situ 3D images that were selected for analysis are labelled as P400, P500, P800 and P1030. At P400, the sample was not broken yet and its image was used as the reference in later analysis. 2D orthogonal images taken from the broken sample are

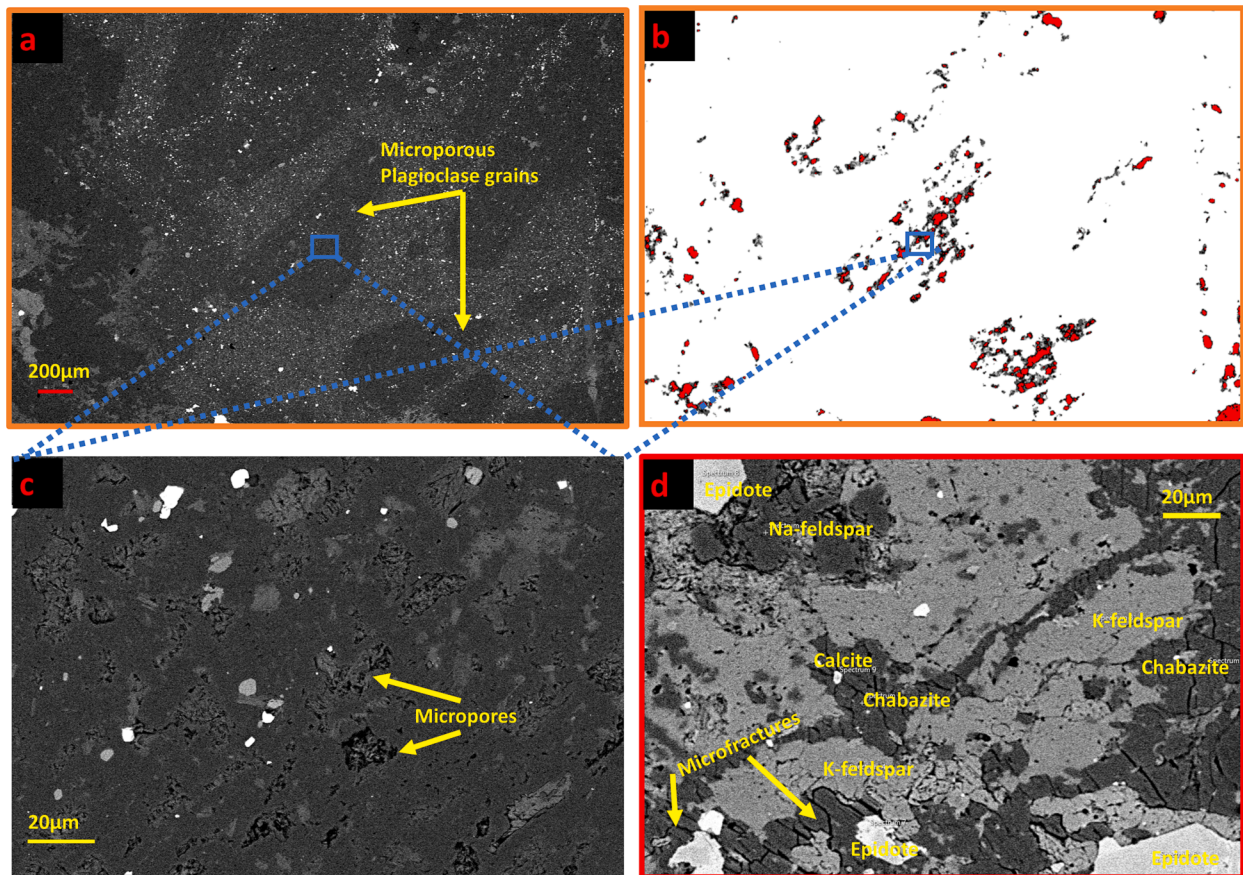


Fig. 10. SEM images (a, c and d) showing minerals and micro-porosities. Images (a) and (d) correspond to the orange and red rectangle areas in the TMQEMSCAN mineral map in Fig. 8, respectively. Image (b) is the corresponding micro-porosity map of image (a), in which red color means micro-porosity greater than 3%. Image (c) is a zoom-in of the blue rectangle area indicated in (a) and (b); it shows the micro-pores inside a plagioclase feldspar grain. Image (d) shows the micro-porosities and mineralogy associated with a vein. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

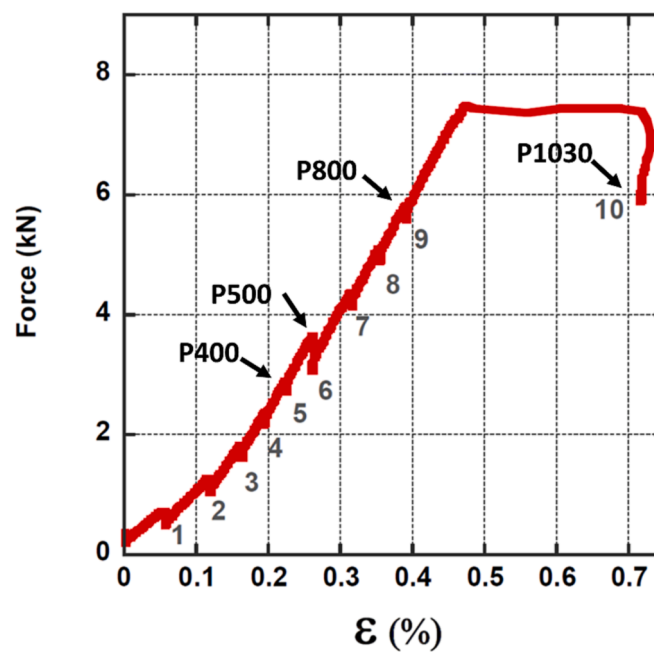


Fig. 11. Force-strain curve measured during the fragmentation test. Numbers 1 to 10 indicate the 10 in-situ images acquired during the test. P400, P500, P800 and P1030 indicate the 4 images that are selected for analysis.

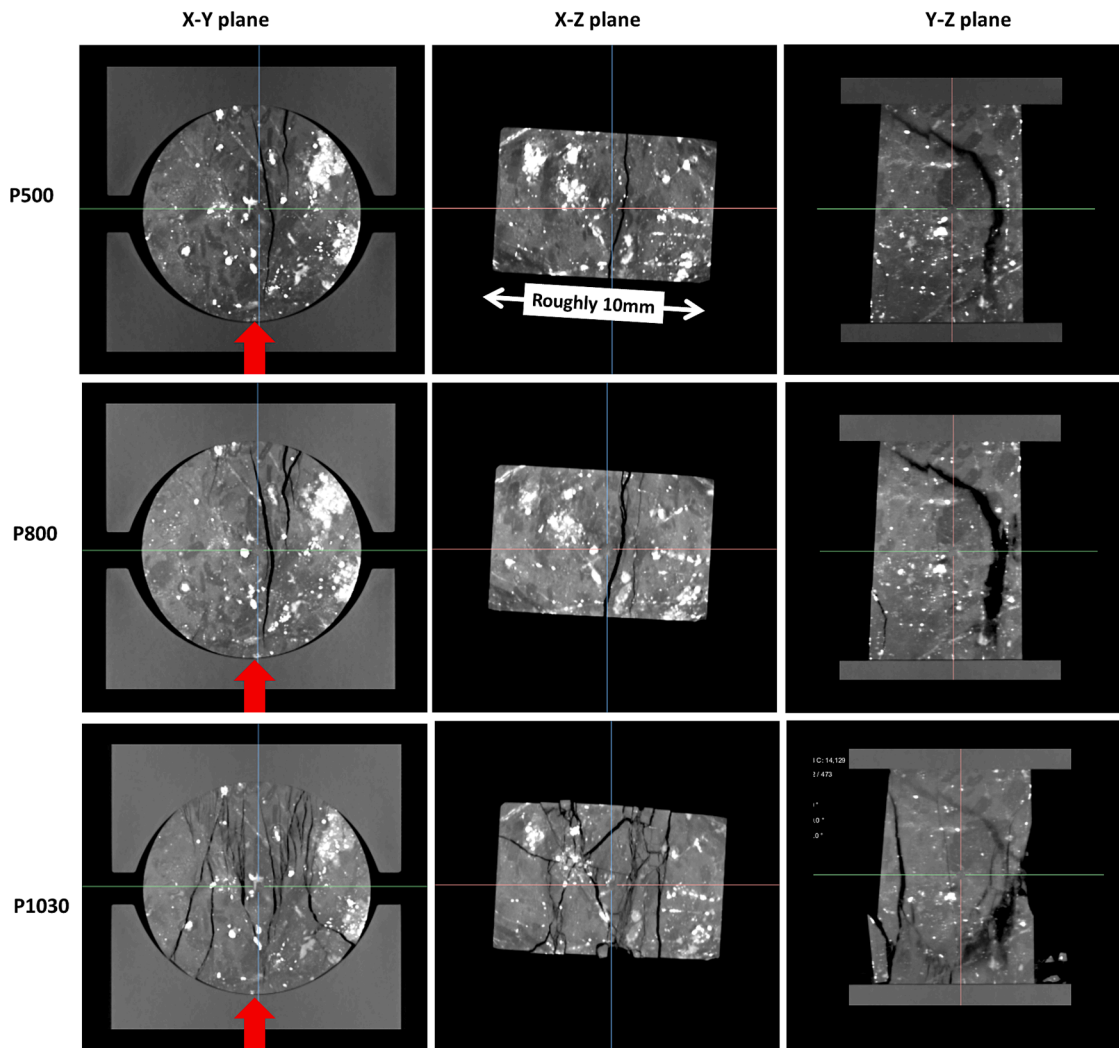


Fig. 12. Orthogonal images taken from 3 breakage steps during the test. Red arrows indicate the direction of loading force exerted on the jaw. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shown in Fig. 12. In Fig. 13, fractures and copper minerals are highlighted by red and orange, respectively. These images reveal the multiple breaking stages that lead to the onset of global fragmentation of the ore (Francois et al., 2006). The first major fracturing occurred approximately along the ore diameter between the loading jaws at a load of 500 psi. It was a result of tensile splitting, as is commonly observed in standard Brazilian tests used in geotechnical studies (Serati et al., 2021). Apart from this central fracture, many smaller scale cracks also appeared near the upper and lower contact regions as a result of compressive stress concentration. After this initial fracturing, more fractures developed throughout the ore sample as the load increased from 500 psi (P500) to 1030 psi (P1030). This produced a complex fracture network. However, it is clear from the images that this breaking process was inhomogeneous with more fractures being developed around the central region, which was partially a result of the jaws geometry.

3.2.2. Fragment size analysis

Fragment separation was undertaken in 3D on P500, P800 and P1030 datasets and results are shown in Fig. 14 by some 2D orthogonal images. At P500 and P800, the fragments were still large and mainly a result of tensile splitting. At P1030, more finer fragments are observed and we refer to this stage as the local comminution stage. This term highlights that the jaws geometry and the complex stress field in the fractured ore gave rise to regions being heavily damaged while some

parts of the rock were barely damaged. In Fig. 14 it is clear that there are large fragments at the periphery of the core at P1030. By contrast, more intensive comminution occurred in the central region, generating some fine fragments. The generation of these small fragments arise from two possible breakage mechanisms:

- 1) from observation of the breakage process and the evolution of the fracture pattern, it is clear that several large central fractures were actually closing up proceeding to P1030 (see Fig. 12) and therefore high compressive and shear stresses might have been produced; the rock-rock friction and compression stresses when the two faces of a fracture come into contact could produce small fragments;
- 2) other regions yielding small fragments are located at the two rock-jaw contact points. Indeed, the geometry of the loading induced compressive stresses concentration at the contact point and this stress concentration is known to influence the failure process and to induce local damages. As the loading increased, this process gave rise to a dense local fracture network.

Fragment size was measured after separation, which was defined as the diameter of the sphere having the same volume as the fragment. Note that this is only a common approximation and that from observation, the shape of the particles is complex. Since the smaller fragments that are of the size of a few voxels are more prone to image artefacts (e.

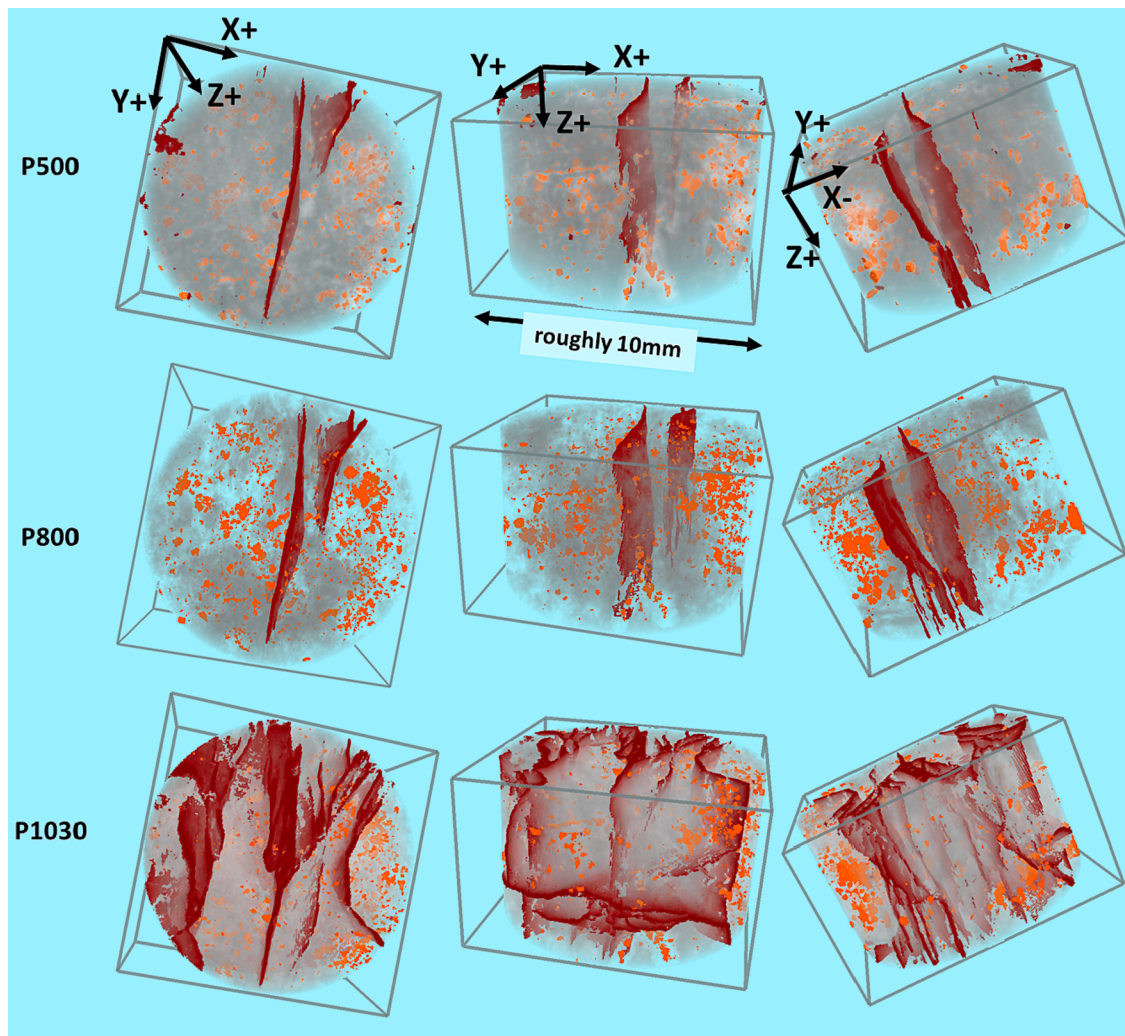


Fig. 13. 3D rendering of the fracture networks developed during the fragmentation test. Fractures are set to red, copper minerals to orange and the rest minerals to grey. Jaws exert load from Y direction and they are not displayed in the fracture rendering. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

g., partial volume effect and blurring), only the fragments with a volume larger than 10^3 voxels (roughly 10^{-3}mm^3) are reported here. This is reasonable since those smaller fragments only account for $<0.1\%$ of the total volume. Fig. 15 (a) shows the evolution of the fragment size distribution during the mechanical test. The total number of fragments increased from 91 at P500, to 228 at P800 and reached 1269 at P1030. The relatively slow increase in fragment number immediately after tensile splitting (from P500 to P800) suggests that this stage of fragmentation was quite limited. Images in Fig. 13 and Fig. 14 show that the fragmentation at this stage was dominated by tensile splitting and compressive breakage near the contact regions with the upper and lower jaws. The sharp increase in fragment number from P800 to P1030 corresponds to the intensive comminution around the central diametrical region which might have involved compression and inter-fragment friction due to fracture closing. For all three loading steps, on average the number of fragments < 1 mm accounts for more than 95% of the total fragment population. However, these fragments represent only 3% of the total volume. As the rock undergoes fracturing, Fig. 15 (b) also reveals the redistribution of the ore volume towards smaller size fractions. For instance, at P800 fragments greater than 1.5 mm accounts for 98% of the total volume and this number drops to 89% at P1030. However, this effect was quite limited as we were only exploring the onset of fragmentation and the vast majority of the rock mass still existed as larger (greater than 1mm) fragments.

3.2.3. Fracture pattern analysis

Microporous regions may provide weak zones within which fractures initiate or propagate more easily. Micro-porosity may also affect the path of a growing fracture due to the anisotropic structure of the micropores. In this section, visual evidences of micro-porosity affecting breakage and fracturing are shown in 3D images. Fig. 16 shows the two major fractures (purple) developed at P500 and phase segmentation of the sample. The smaller fracture, as indicated by the black arrow, will be focused since this secondary fracture (as opposed to the major tensile splitting fracture) seems to be affected more evidently by micro-porosity.

Fig. 17 shows a region of interest with micro-porosity map overlaid on phase segmentation where brown color means micro-porous regions. These XY slices show one example where fracture path was affected by the micro-porous plagioclase grains. From left to right, the images move towards Z + direction in 3D. The black arrows point to that the fracture deviated to cut along the boundary of a plagioclase grain (denoted by P) and then got a little bit inside of the grain (still close to the boundary) before left the it along the boundary again. This fracture pattern suggests a weak grain boundary after the development of micro-porosity. Note that this example is only to demonstrate that fracturing path could be affected by micro-porosity. Whether this grain boundary breakage is dominant or not for the whole sample will be discussed in section 3.2.4.

Fig. 18 shows similar information as in Fig. 17 by putting phase

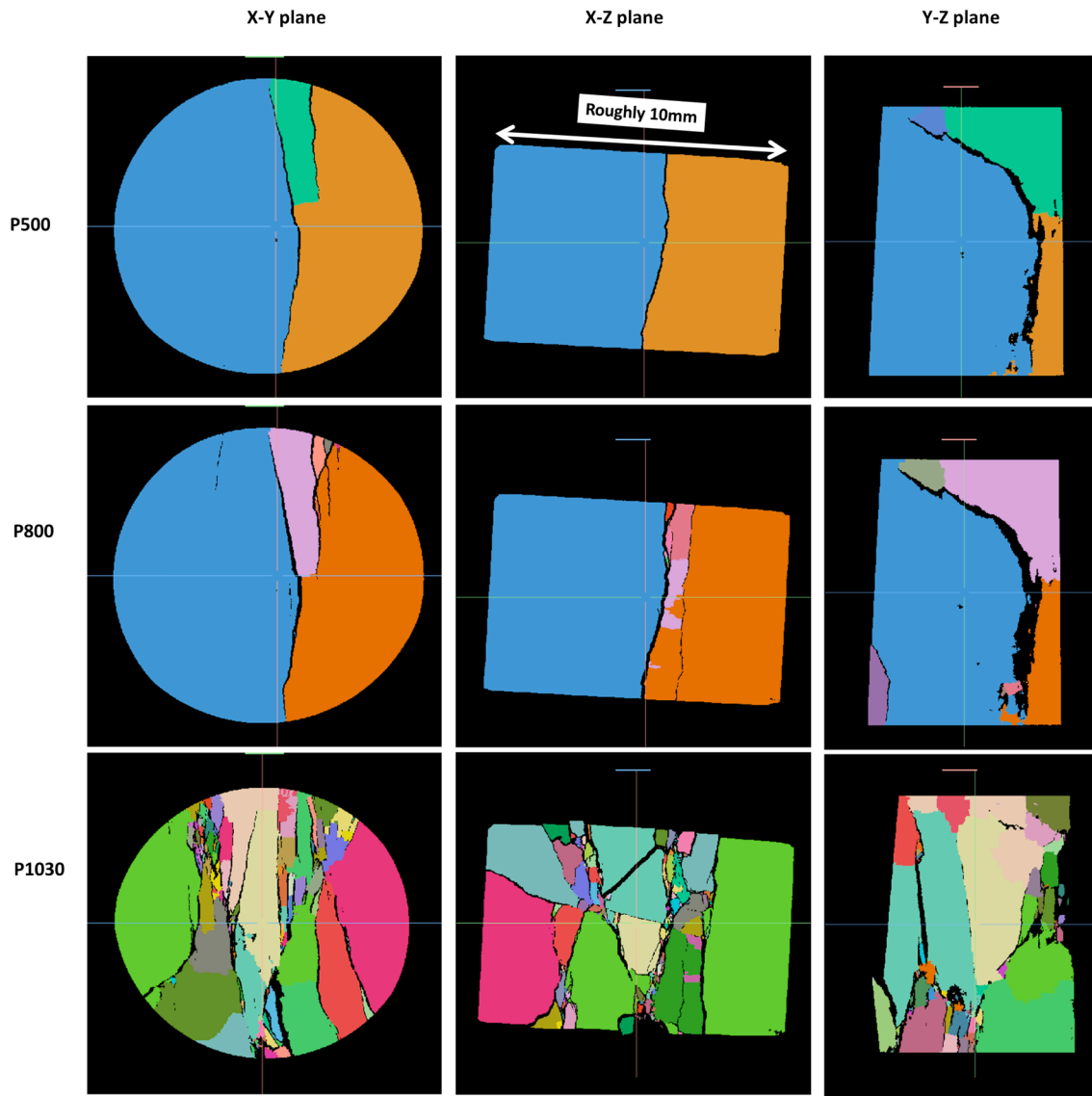


Fig. 14. Fragment (or particle) separation results shown by orthogonal slices from each of the 3 datasets. Each color in a dataset represents a fragment. Note that sample diameter was not exactly 10 mm during fragmentation test due to breakage and movement.

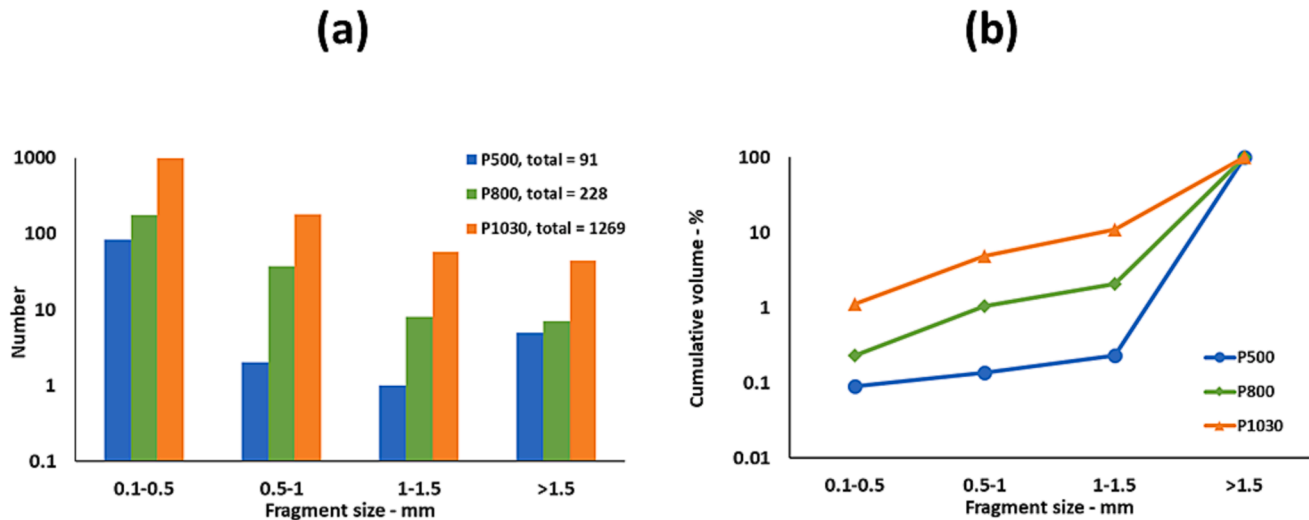


Fig. 15. (a), fragment size distribution. (b), cumulative fragments volume Vs. fragment size. For simplicity, each fragment was treated as a sphere of equal volume and fragment size was taken as the diameter of the sphere.

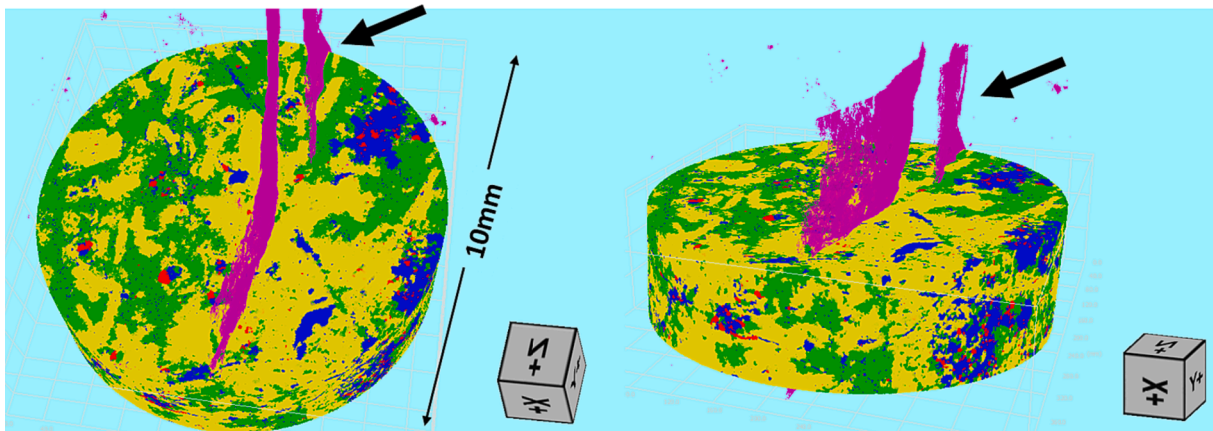


Fig. 16. 3D visualisation of two major fractures (purple color) at loading step P500. The sample is shown in terms of segmentation. Yellow phase: plagioclase and quartz; green phase: alkali feldspar; blue phase: epidote and minerals associated with veins; red phase: copper sulphide minerals. Black arrow indicates the smaller fracture that will be discussed in more detail later. Note that top half of the sample was set to invisible in order to show the fractures more clearly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

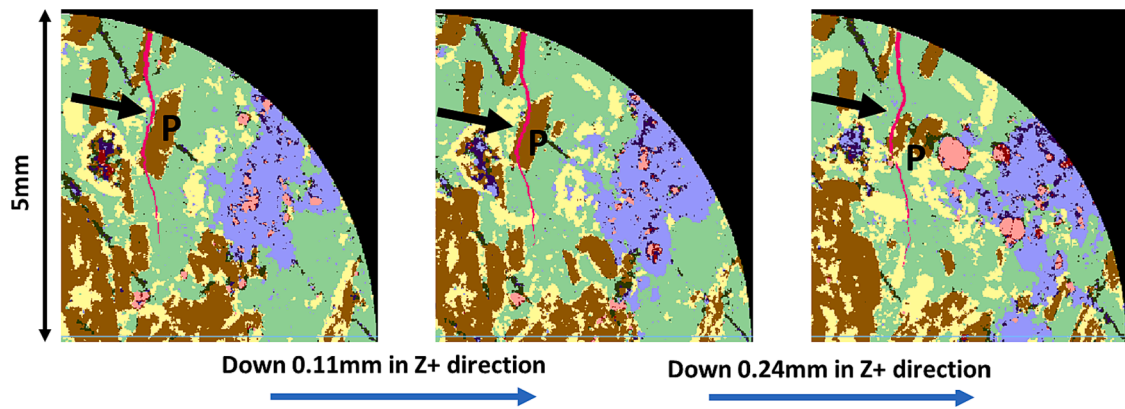


Fig. 17. XY slices showing fracture (purple) and phase segmentation on a subset of the data, overlaid by micro-porosity map (brown color). P indicates a microporous plagioclase grain. Black arrows point to the fracturing along plagioclase grain boundaries. For segmentation: yellow phase: plagioclase and quartz; green phase: alkali feldspar; blue phase: epidote and minerals associated with veins; red phase: copper sulphide minerals. The colors for segmentation are a bit distorted after covered by micro-porosity map. Note that some parts of the sample were set to invisible in order to show the fractures more clearly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

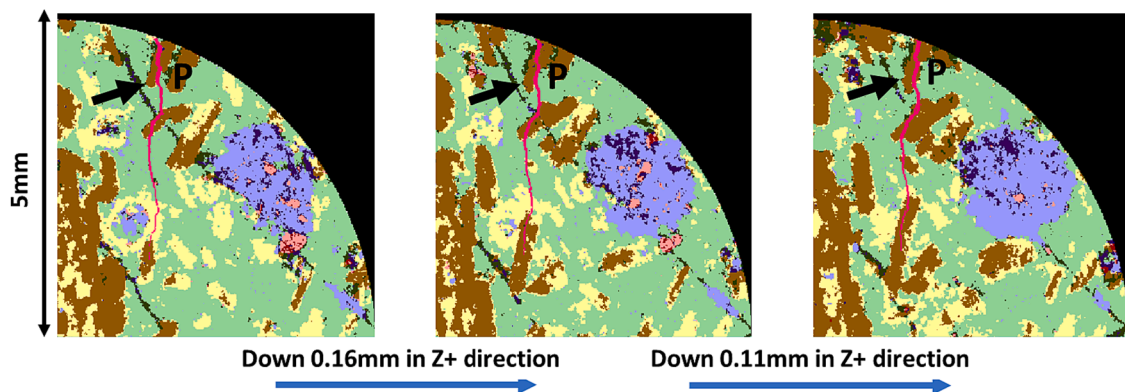


Fig. 18. XY slices showing fracture (purple) and phase segmentation on a subset of the 3D data, overlaid by micro-porosity map (brown color). P indicates microporous plagioclase grains. Black arrows point to the change of fracture pattern inside a plagioclase grain. For segmentation: yellow phase: plagioclase and quartz; green phase: alkali feldspar; blue phase: epidote and minerals associated with veins; red phase: copper sulphide minerals. The colors for segmentation are a bit distorted after covered by micro-porosity map. Note that some parts of the sample were set to invisible in order to show the fractures more clearly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

segmentation and micro-porosity map together. These XY slices demonstrate a case where a fracture was affected by the micro-structure of a plagioclase grain. It is interesting to note the changes of orientation of the fracture inside the grain with a characteristic 90° zigzag pattern (indicated by the black arrows). This pattern is similar to the cleavage steps observed by Zhang and Zhao (Zhang and Zhao, 2014). Feldspar (including plagioclase) grains have 2 cleavage planes that are orthogonal; after chemical alteration these planes can be even weaker and provide the weakest path to fracturing. It seems that the fracturing inside the grain followed the weak cleavage planes before leaving the grain along this boundary.

3.2.4. Breakage type characterization by ore texture analysis

The coupling between breakage and ore texture was quantified using the new ore texture analysis method, PIAM, as proposed in section 2.4. In order to do this analysis, phase interfacial areas were calculated in 3D from segmentation datasets. PIAM results before breakage (P400) are shown in the left matrix of Fig. 19. Since it is assumed that the sample was surrounded by air at the beginning, the interfacial areas between fracture (air) and minerals at P400 indicate the exposure of the minerals on the outer surface of the intact sample. What is more important is the interfacial areas between minerals before breakage because they give textural information of the sample. For a better understanding of the preferential contact relationships, the left matrix of Fig. 19 is rearranged to get the right matrix, which quantifies phase contact relationships after normalization by phase volume fractions. It is found that the copper sulfide minerals (the red phase) are mostly (90%) in contact with epidote (the blue phase). The minerals of the yellow phase (mainly plagioclase and quartz) show a strong contact preference with the green phase (alkali feldspar). In contrast, the alkali feldspar has a more even

contact relationship with the other minerals, i.e., 34%, 42% and 24% with plagioclase + quartz, epidote and copper sulfides, respectively.

PIAM results for the progressive breaking of the sample are shown in Fig. 20 and some of the data is further analysed in Fig. 21. Breakage types can be analysed based on the data shown in Fig. 20. As an example, breakage types associated with the yellow phase (mainly plagioclase and quartz) are analysed by comparing the loss of yellow-green, yellow-blue and yellow-red interfacial areas against the increase of yellow-fracture interfacial area. Taking P400 and P1030 datasets as an example, the yellow-green (plagioclase + quartz and alkali feldspar) interfacial area lost 183 mm² (from 4284 to 4101 mm²), yellow-blue (plagioclase + quartz and epidote) lost 37 mm² (from 145 to 108 mm²) and yellow-red (plagioclase + quartz and copper sulfides) lost 3 mm² (from 23 to 20 mm²), which is a total loss of 223 mm². This loss of interfacial area between the yellow phase and its neighbouring minerals indicates and quantifies a breakage Type I which produced an equivalent increase of 223 mm² of the interfacial area between yellow phase and fracture. In the meantime, the total increase of yellow-fracture interfacial area was 787 mm² (from 201 to 988 mm²), which is 564 mm² more than 223 mm². This indicates that breakage Type II also occurred to the yellow phase and increased yellow-fracture interfacial area by 564 mm². Comparing the increase of yellow-fracture interfacial area from different types of breakage, reveals that breakage of Type II was the dominant mechanism for the yellow phase.

Fig. 21 (a) shows the changes of interfacial area between 6 pairs of minerals. It confirms that no significant decrease of minerals interfacial area occurred. This suggests that the breakage was mainly Type II, i.e., internal breakage. Fig. 21 (b) shows the increased fracture-mineral interfacial area (expressed in % of the total surface created) at each loading step compared with the pre-failure rock state (P400). More than

	Fracture	Yellow	Green	Blue	Red
Fracture	—	201	271	38	2
Yellow	201	—	4284	145	23
Green	271	4284	—	1517	162
Blue	38	145	1517	—	213
Red	2	23	162	213	—

Rearrangement →

	Fracture	Yellow	Green	Blue	Red
Fracture	—	—	—	—	—
Yellow	—	—	63%	20%	17%
Green	—	34%	—	42%	24%
Blue	—	3%	12%	—	85%
Red	—	3%	7%	90%	—

Fig. 19. Left, phase interfacial area matrix (PIAM) for P400, before breakage. To get the right matrix, the first row and first column of the left matrix are omitted; then, numbers in the left matrix are firstly normalized by their corresponding phase volume fraction and then each row is normalized (the sum of each row is 100%). Yellow phase: plagioclase and quartz; green phase: alkali feldspar; blue phase: epidote and minerals associated with veins; red phase: copper sulphide minerals.

	Fracture	Yellow	Green	Blue	Red
Fracture	—	201	271	38	2
Yellow	201	—	4284	145	23
Green	271	4284	—	1517	162
Blue	38	145	1517	—	213
Red	2	23	162	213	—

P400

	Fracture	Yellow	Green	Blue	Red
Fracture	—	303	414	63	6
Yellow	303	—	4364	141	21
Green	414	4364	—	1504	159
Blue	63	141	1504	—	211
Red	6	21	159	211	—

P500

	Fracture	Yellow	Green	Blue	Red
Fracture	—	394	506	69	7
Yellow	394	—	4236	132	22
Green	506	4236	—	1353	162
Blue	69	132	1353	—	202
Red	7	22	162	202	—

P800

	Fracture	Yellow	Green	Blue	Red
Fracture	—	988	1402	124	16
Yellow	988	—	4101	108	20
Green	1402	4101	—	1331	158
Blue	124	108	1331	—	194
Red	16	20	158	194	—

P1030

Fig. 20. Phase interfacial area matrices (PIAM) for the 4 datasets selected for breakage characterization, as shown in Fig. 12. Yellow phase: plagioclase and quartz; green phase: alkali feldspar; blue phase: epidote and minerals associated with veins; red phase: copper sulphide minerals.

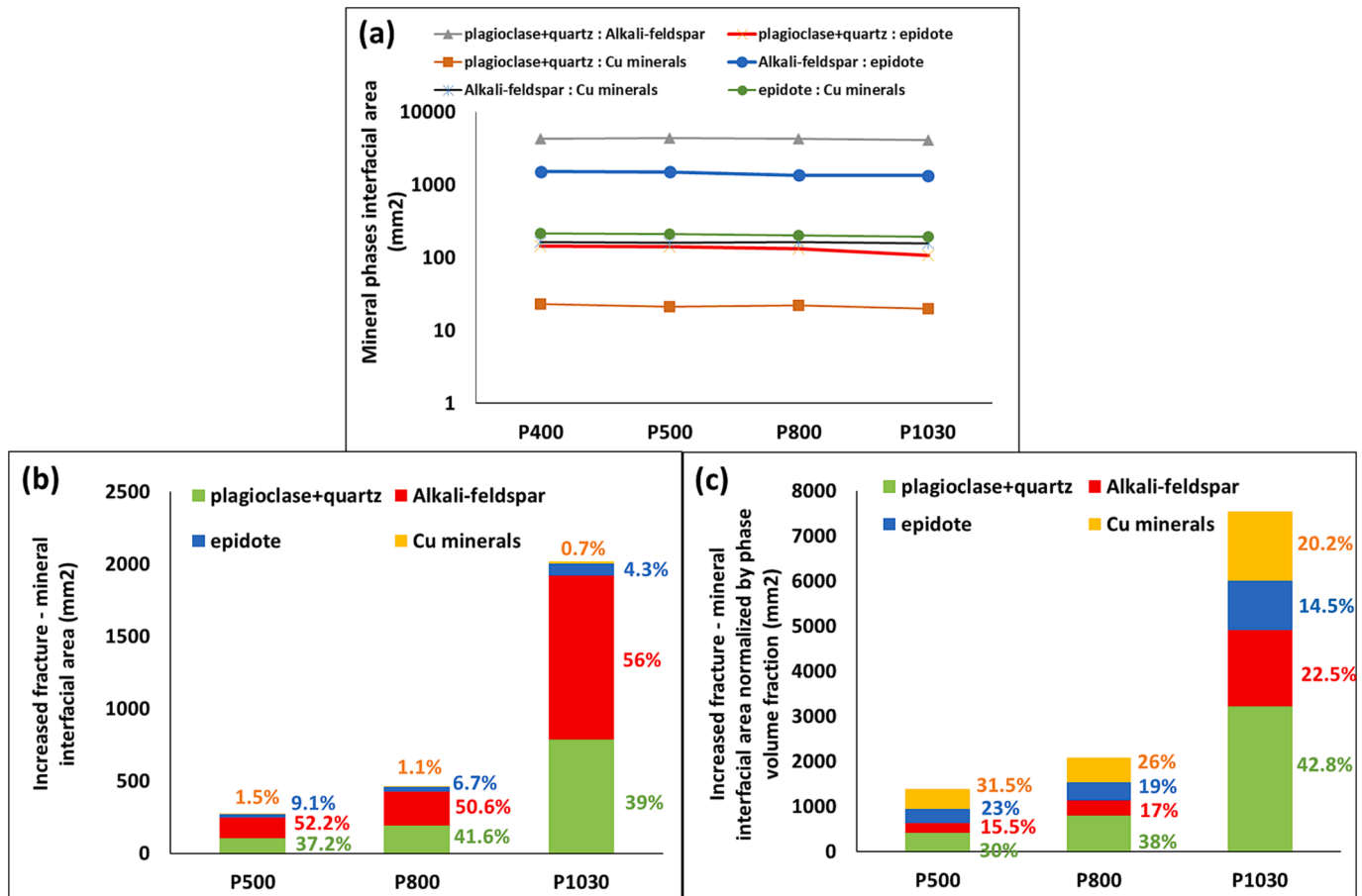


Fig. 21. (a) interfacial areas between mineral phases; (b), increased interfacial areas between fracture and mineral phases compared with P400; (c) same as (b) but normalized by phase volume fraction. Data used here are the same as or derived from the data given in the matrices in Fig. 20.

50% of the increased fracture-mineral interfacial area was associated with the alkali feldspars for all loading steps. However, these numbers need to be normalized by the corresponding phase volume fraction, which are shown in Fig. 21 (c). After normalization it is found that there was a preference of fracturing in the yellow phase (containing plagioclase and non-porous quartz), especially at P1030 where it contributed 42.8% of the increased fracture-mineral interfacial area. This data reveals that the yellow phase was the most easily damaged phase. Note that since plagioclase and quartz cannot be distinguished from each other under current imaging settings, it is not clear how much of the breakage was associated with plagioclase or quartz alone. Since the yellow phase shows the most pronounced micro-porosity, which is mainly from the micro-porous plagioclase, it is reasonable to assume that micro-porous areas behaved as weak zones that tend to promote breakage.

3.2.5. Copper minerals surface liberation

Fig. 22 shows the evolution of Cu minerals surface liberation during the ore fracturing up to the onset of fragmentation. The graphics also show the reduction of the average size of the fragments larger than 1 mm, which account for 97% (on average) of the total sample volume (see Fig. 15 b). The surface liberation of the Cu minerals phase increased slowly as the sample was broken gradually. The largest increase in liberation occurred in the local comminution stage, corresponding to the sharp increase of fracture-mineral interfacial area (from ~ 500 to ~ 2000 mm², Fig. 21 b) where the number of fragments increased by a factor of 5 (Fig. 15 a). Final surface liberation of the Cu minerals phase was low, only reaching 4.1% at P1030. One reason for this low liberation is related to the fact that the fragmentation test carried out here was only

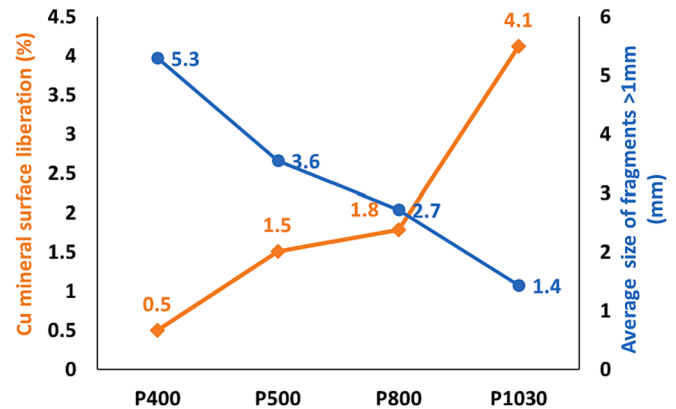


Fig. 22. Cu minerals surface liberation curve with average fragment size at each loading step. Fragment size was taken as diameter of the sphere having the same volume of the fragment. Cu minerals surface liberation before breakage is due to exposure of the copper minerals on the outer surface of the intact sample.

a coarse size reduction process. Higher liberation often requires further grinding of the fragments; our test had just reached the onset of the fragmentation.

Nevertheless, this pilot model experiment demonstrates that in-situ mechanical crushing enables us to quantitatively study the coupling of ore texture and breakage characteristics in mineral liberation. For instance, texture analysis from the intact sample shows that 90% of the Cu minerals was in contact with epidote, 7% with alkali feldspars and

3% with plagioclase + quartz. Preferential breakage associated with the epidote phase would be desirable because it would liberate more copper minerals. However, the PIAM analyses (Fig. 21 c) show that breakage mainly occurred in the alkali feldspar and plagioclase + quartz phases while the epidote phase only accounted for <20% of the total fracture-mineral contact area. This implies that the copper mineral grains mainly embedded in the epidote were more difficult to liberate. In addition, only 3% of the Cu minerals were in contact with the weaker plagioclase + quartz phase. This poses another intrinsic limitation for this sample that prevented a higher Cu mineral liberation. These findings suggest that while the extent of size reduction (i.e., particle size) is certainly a key factor that controls mineral liberation, ore texture and breakage characteristics should also be considered (Lund et al., 2015).

4. Conclusions and future work

This study provides a quantitative method that is cable of breakage behaviour characterization of copper ores. Using the custom-built XCT-HP apparatus at the ANU (Vizcarra et al., 2010), one porphyry copper ore sample was studied in 3D as it was fragmented. High resolution 3D images were acquired at different stages of the fragmentation test, which allowed us to track the evolution of the breakage process. After image segmentation, which was guided by TMQEMSCAN mineral maps, texture analysis was performed using phase interfacial area as a descriptor. By comparing the phase interfacial area matrices (PIAM) at different loading steps, breakage types of the dominant phases and liberation of the Cu-sulfides were quantified. 3D mapping of micro-porosity was also undertaken to investigate its role in fragmenting the ore sample.

The conclusions of this study are:

1. For the particular ore sample used, the effects of micro-porosity on breakage were studied. The most porous phase, containing plagioclase and quartz, was the most damaged phase during the fragmentation. Cases where the micro-porous plagioclase grains have impacts on fractures pattern were observed. Fracturing along plagioclase grain boundaries and the cleavage directions indicate weak grain boundaries and weak cleavage planes after alteration, respectively. However, as discussed in section 3.2.4, these preferential breakages were not the dominant breakage type for the whole sample during this test.
2. The quasi-static breaking process involved two stages of size reduction: tensile splitting and local comminution. The tensile splitting stage is characterized by a central fracture and a few large fragments (greater than 1mm) that account for over 99% of the total volume; the subsequent local comminution stage showed a large number of smaller fragments (<1mm) that only account for ~ 5% of the total volume.
3. Tracking the changes of phase interfacial area (in the form of PIAM) is an effective tool for distinguishing and quantifying different breakage types. For the ore sample used in this study, PIAM suggests that Type II (internal) breakage was the dominant breakage type for the alkali feldspar and plagioclase + quartz phases. For the plagioclase + quartz in particular, Type II occurred 2.5 times more often than Type I (phase boundary) breakage. Further improvement on image contrast and using machine learning methods for better image segmentation (Wang et al., 2021; Guntoro et al., 2019) could be used in the future to improve the PIAM method. This in particular may improve the breakage characterisation of the less dominant minerals.
4. Surface liberation of the Cu sulfides reached 4.1% at the end of the fragmentation test. On one hand, the low liberation is due to the fact that the test only reached the onset of global fragmentation. Higher liberation requires further breaking and size reduction. On the other hand, Cu sulfides liberation is also controlled by texture and breakage characteristics of the ore sample: only 3% of the Cu minerals are in contact with the most easily broken phase (plagioclase + quartz), while 90% of the copper-containing grains are in contact

with the epidote which is more resilient to fracturing. This highlights the importance of studying ore texture and breakage characteristics for more energy efficient mineral liberation.

CRediT authorship contribution statement

Yulai Zhang: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Nicolas Francois:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Richard W. Henley:** Conceptualization, Investigation, Writing – review & editing, Supervision. **Lydia Knuefing:** Conceptualization, Methodology, Writing – review & editing. **Michael Turner:** Investigation, Writing – review & editing, Resources. **Mohammad Saadatfar:** Conceptualization, Writing – review & editing. **Frank Brink:** Visualization, Writing – review & editing. **Mark Knackstedt:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Yulai Zhang reports financial support was provided by Australian Research Council.].

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.mineng.2023.108464>.

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