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Understanding selectivity in radio frequency and microwave sorting of porphyry copper ores

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Abstract

Continuous high-throughput microwave treatment followed by infrared thermal imaging (MW-IR) has previously been shown to provide attractive separations for a number of porphyry copper ores, leading to rejection of a large proportion of barren fragments from ore-grade material or concentration of copper values from waste-grade material. However, the efficacy of the sorting process is reduced by the presence of hydrated clays and pyrite. Literature measurements have shown differences in the conductivity of pyrite and copper sulphides such as chalcopyrite at radio frequencies. In this work the potential of using radio frequency (RF) heating to exploit these differences and achieve improved selectivity between copper and iron sulphides, is investigated. For the first time a novel bulk materials handling and presentation method that facilitates even heating of angular ore fragments in parallel plate RF systems is discussed. The fragment-by-fragment thermal response of five ore samples under equivalent pilot MW-IR and RF-IR processing conditions is evaluated, showing that there is an increase in selectivity in the heating of hydrated clay minerals in RF compared to microwave. It is suggested, again for the first time, that selectivity in the microwave processing of ores containing semi-conducting minerals is due predominantly to magnetic absorption (induction heating) caused by eddy currents associated with the magnetic field component of electromagnetic energy. In radio frequency processing, where electric field is the dominant component, heating of semi-conducting minerals is limited by the electric field screening effect. This effect is demonstrated using synthetic fragments. Thermal response profiles of synthetic fragments show that approximately 2.5 times the mass of sulphide minerals to hydrated clay minerals would result in an equal temperature increase for microwave heated fragments in which the microwave-heating minerals are evenly disseminated throughout the matrix. This understanding provides the foundations for development of models incorporating different thermal responses for individual heated phases, alongside other textural and treatment variables, that can be used to predict how close to intrinsic sortability ores will perform in MW-IR and RF-IR without the need for extensive processing trials.

Keywords

microwave, radio frequency, ore, copper, sorting, infrared

1 Introduction

In recent years sorting of ores has seen renewed interest, as a means of reducing comminution energy, with many studies demonstrating the potential benefits of applying sensor based sorting to mineral processing operations (Tong et al., 2015, Norgate and Jahanshahi, 2010, van Berkel, 2007, Pokrajcic et al., 2009, Lessard et al., 2014). For large scale, low grade operations such as porphyry copper processing, pre-concentration to reject uneconomic material prior to the energy intensive grinding stages has the potential to significantly improve the sustainability of operations. These improvements could be realised by an increase in the grade to the concentrator (and therefore copper output) and a reduction in the copper specific energy consumption in comminution and water usage in processing (Salter and Wyatt, 1991). Sensor based sorting on a fragment by fragment basis also provides an opportunity to scavenge valuable material from waste; the extent of waste as a resource was demonstrated in a study by Klein and Mazhary (2015) which showed that 25% of waste dump material from two porphyry deposits was of a high enough grade to be economically processed. Key to unlocking the potential of ore sorting is selection of appropriate discrimination sensor technologies. Many sensors currently proven at industrial throughputs rely on surface techniques, which for highly heterogeneous ores such as those found in porphyry copper deposits, do not give suitable separations for sorting (Tong et al., 2015).

Microwave heating followed by infra-red thermal imaging (MW-IR) has been investigated as a potential excitation-discrimination technique for sorting of ores (Van Weert and Kondos, 2008, Van Weert et al., 2011, John et al., 2015, Ghosh et al., 2013, Ghosh et al., 2014). Microwave energy provides selective and volumetric heating of certain mineral phases within the ore matrix; semi-conductive minerals such as nickel, copper, iron and lead sulphides, oxides such as magnetite and other minerals with bound and/or free water (e.g. smectite clay) heat far more readily than common rock-forming minerals, such as quartz, feldspars, calcite and micas (Walkiewicz, 1988, McGill et al., 1995, Chunpeng and Yixin, 1996, Harrison, 1997). Measurement of individual surface average temperature of fragments then provides a basis for discriminating between valuable and uneconomic material.

The pilot scale sorting performance of 16 porphyry copper ores has been investigated using a high throughput 100t/h belt based 100 kW microwave system designed to operate together with commercially available sorting modules (Batchelor et al., 2016). Overall, the best performing ores under MW-IR were those with a low average moisture content and co-mineralisation of copper and iron sulphides. On the other hand, abundance of microwave heating gangue minerals, such as iron sulphides, iron oxides and hydrated clays, reduced the efficacy of the sorting process.

Radio frequency electromagnetic energy is longer in wavelength than microwave energy; for the relevant industrial, scientific and medical (ISM) bands this difference equates to 11m at 27.12 MHz RF compared to 33cm at 896 MHz microwave. The electromagnetic heating properties of materials vary with frequency. Measurements of the radio frequency conductivities of selected sulphides and iron oxides by Genn and Morrison (2014) suggest favourable differences between the electromagnetic heating of copper and iron sulphide minerals may be observed at radio frequencies, compared to the microwave range. These measured differences in conductivity of pyrite and chalcopyrite suggest that electromagnetic processing of porphyry copper ore fragments at radio frequencies rather than microwave frequencies should lead to increased heating of chalcopyrite compared to pyrite. Achieving this improved selectivity during the sorting process could lead to sortability performance for ores closer to their intrinsic potential. However, the effect of varying electromagnetic frequency, specifically the use of radio frequency (RF) excitation has not been considered in the literature with respect to ore sorting based on heating effects.

The objective of this paper is to determine for the first time the potential of using RF-IR excitation-discrimination to sort porphyry copper ores on a fragment by fragment basis and investigate whether improved selectivity of copper sulphide minerals can be achieved compared to MW-IR. A novel method for materials handling during bulk RF excitation is developed that allows the fragment-by-fragment thermal response following microwave and RF treatment to be evaluated. Using this method the difference in the thermal response of fragments during microwave and RF processing is determined and evaluated with respect to the mineralogy of the ore fragments. Using synthetic fragments, the electric and magnetic field contributions to the overall heating of sulphide and clay minerals at microwave and radio frequencies are evaluated, and the implications these findings have for optimising selectivity in industrial scale ore sorting based on MW or RF-IR excitation and discrimination are discussed.

2 Materials and methods

2.1 Sample mineralogy, preparation and characterisation

Five porphyry copper ore samples were processed in this investigation, all originating from the same host site. The five samples were two ore and two waste grade feeds with varying lithologies, plus a recycled pebbles sample. Bulk ore samples (~200kg) were supplied in three narrow size classes, namely -65.5+50.8mm, -50.8+25.4mm and -25.4+12.7mm. These size classes are based on the requirements for compressed air jets that would be used to blast fragments during separation in industrial ore sorting processes. Each 200kg barrel was split using a rotary sample divider to provide sub samples of 240 fragments. Each fragment was heated individually in a microwave cavity and infra-red images for each fragment analysed. Each fragment was then cut in half and each half retested in the microwave; if each half was shown to have equivalent thermal responses the fragment progressed to the next stage of preparation. For equivalent halves, one was kept for sorting tests whilst the other was pulverised to -75µm to produce powders for elemental and moisture analysis. For each ore type tested, a set of 72 fragments were produced across the three size classes and were selected to give a range of thermal responses. The samples were produced in this manner to be indicative of the extremities of thermal responses that could be observed within a particular ore. Fragments were classified according to copper content and temperature rise within the wider test sample. For each ore sample, the hottest 30% of fragments by mass and the richest (Cu) 30% by mass were used to determine response thresholds, and fragments classified as true negative, false negative, true positive and false positive. For example true negatives were low copper content fragments (lowest 70% Cu by mass) that exhibited a low temperature rise (coldest 70% by mass). This selection methodology minimised the number of fragments with very complex compositions, allowing the mineralogical reasons for thermal responses to be elucidated. However because of the selection method used, it should be noted that the sample grade and thermal responses are not representative of the bulk ore as a whole. Individual fragment copper, sulfur and iron content were determined using powder XRF. Chalcopyrite and pyrite content for each fragment was calculated from stoichiometry, assuming these were the only sulphides present (see Table 1). Moisture analysis was performed using thermo-gravimetric analysis (TGA) to heat a small sub-sample (~20mg) of the pulps to 120°C. The sample was held at 120°C for 5 minutes to allow the vast majority of the free water to be driven off. 120°C was chosen to remove the vast majority of free water without altering the chemical structure of the clays. Moisture analysis reproducibility testing of five subsamples from a single ore fragment yielded a standard deviation of 6.6% between measurements (0.380 ± 0.025 Wt%) which was deemed sufficient for the purposes of this investigation.

Table 1 Ore lithology and major heated phase content

Ore	Lithology	Chalcopyrite Average Weight %	Pyrite Average Weight %	Free water Average Weight %	Total Average Weight %
1	Limestone Skarn	0.90	10.45	0.49	11.85
2	Quartzite (Waste)	0.75	1.99	0.20	2.93
3	Quartz-monzonite	1.57	5.34	0.27	7.18
4	Quartz-monzonite (Waste)	0.50	3.25	0.70	4.46
5	Recycled pebbles	0.56	1.47	0.72	2.75

2.2 Pilot scale continuous MW treatment of ores

Continuous microwave treatment of samples was carried out using the pilot scale 100kW 896 MHz system and processing methodology described in detail in (Batchelor et al., 2016). The test fragments were spread across the full width of the microwave belt in a closed monolayer (100% belt coverage) arrangement within a bed of fill material of the same ore. The fill material was chosen to be the -50.8+25.4mm size class as this most closely approximated the average size of the 72 test fragments in each sample. Fragments were treated in two different orientations at target microwave energy inputs of 0.7 kWh/t. This dose was achieved by selection on an appropriate belt mass loading, belt speed and microwave power for each ore.

2.3 Pilot scale batch RF treatment of ores

Radio frequency testing of ores and synthetic fragments was carried out in a 20kW 27 MHz Sairem 50Ω radio frequency system. The system provides a highly homogenous electric field between two parallel plate electrodes measuring 440x1200mm. Test fragments were placed in a plastic tray in the chosen orientation. Three trays of sacrificial material were used to fill the remaining belt space between the RF electrodes. Fill material was of the same ore as the test sample, and the size class was chosen to closely match the height of the test fragments. The total mass of ore in each tray of fill material was kept within ±5% of the mass of the test fragments sample tray, to minimise changes in treatment times and provide an even load between the electrodes. The electrode height was fixed at 5mm above the tallest fragment. A vector network analyser (VNA) was used to pre-match the impedance of the load and the RF generator, to determine parasitic losses and maximise absorbed power. Fragments were treated statically between the electrodes for a set exposure time and power, to give the required dose of 0.7 to 1.0 kWh/t. Parasitic energy losses within the system were <2% and therefore assumed to be negligible. Power absorbed into the ore was calculated as the difference between forward and reflected power. Figure 1 presents a schematic of the monolayer treatment.

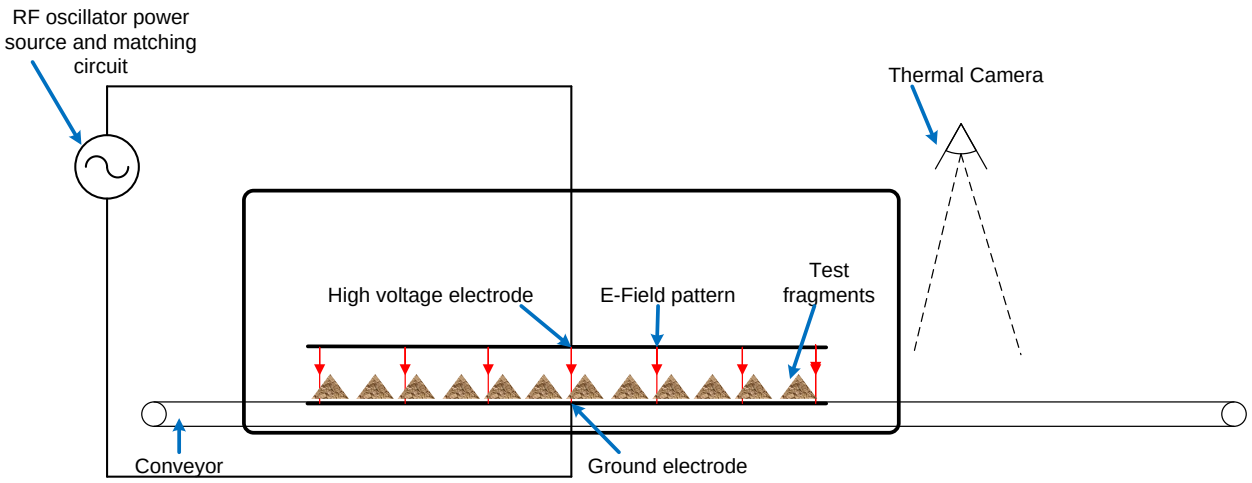

Figure 1: RF treatment apparatus for batch monolayer testing

2.3.1 Developing a method for fragment presentation in RF treatment

It was observed during initial scoping tests of ore fragment monolayers in the RF parallel plate system that hot points were occurring on the edges and tips of fragments located closest to the upper electrode. Ferrari-John et al. (2016) conducted an investigation into the specific effects of geometry on the heating profiles of irregular shaped loads. The presence of edges and vertices on angular particles, and their proximity to faces perpendicular to RF parallel plate electrodes, increased localised heating, due to electric field concentrations at these locations. For angular particles with homogenous dielectric properties, this localised heating was shown to dominate temperature rise; particles of the same geometry processed in different orientations exhibited different heating profiles (Ferrari-John et al., 2016). This effect in the heating of ore fragments is shown in Figure 2. A fragment thermal response related to angularity and orientation rather than mineral content in an RF-IR sorting process would have a negative impact on actual sortability performance. To use RF-IR to discriminate between ore fragments based on mineralogical composition rather than geometry, development of a method to overcome these shape effects was required.

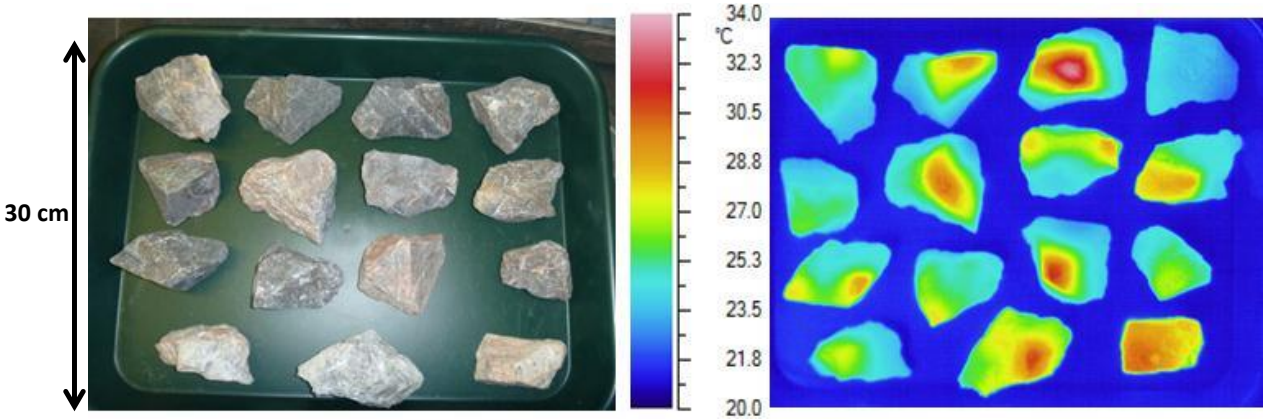

Figure 2 Sample photo and IR thermal image of angular fragments following monolayer treatment in parallel plate RF system

A method for rotating a packed bed of material within the RF cavity was devised that was found to largely mitigate the effect of fragment geometry. The test fragments were placed in a cylindrical plastic tube and surrounded by crushed fill of the same ore type to cover the full length of the electrodes. The sample tube was plugged to prevent any spillage or movement of the packed bed during treatment. An empty length of the sample tube extended out of the RF tunnel so the tube could be manually rotated during treatment. By surrounding the test fragments with crushed fill material of the same ore type, electric field concentrations on tips and edges are minimized as power is absorbed into the surrounding material as well as the test fragments. By also rotating the bed of material (at approximately 15 rpm), tips and edges are no longer in a static position and the presentation of the fragments to the electric field is constantly changing. Tubes of sacrificial material of the same ore type and mass were placed alongside the sample tube in the tunnel to provide an even load between the electrodes. Total energy input was scaled by increasing the treatment time, and power, to provide a comparative energy dose to monolayer treatments. The rotating packed bed testing schematic is presented in Figure 3.

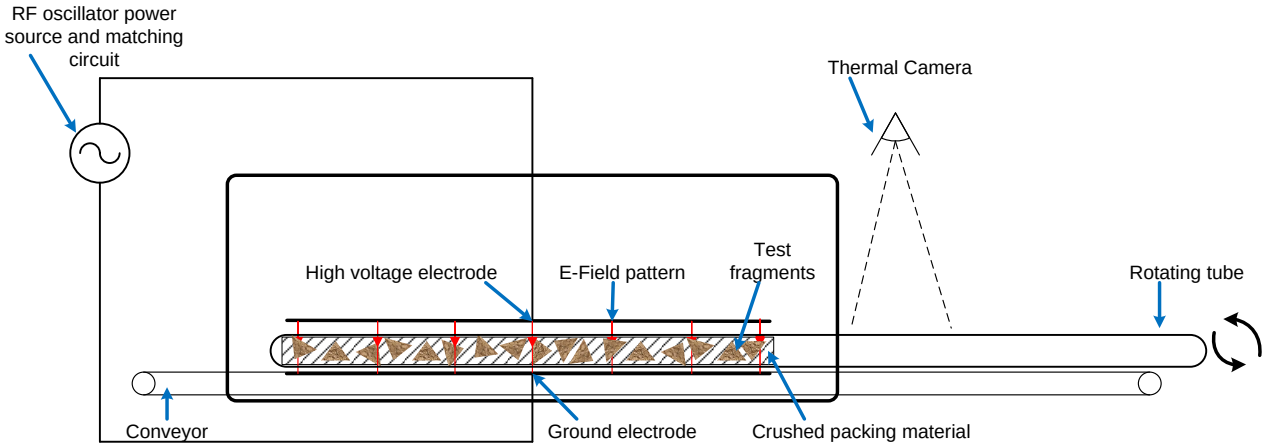

Figure 3: RF treatment apparatus for batch rotating packed bed testing

2.4 Thermal image analysis

The thermal response of ore and synthetic fragments following microwave or RF treatment was captured using an NEC H2640 thermal imaging camera. For each recorded test run with any excitation method, a thermal image was taken immediately prior to treatment. After treatment, thermal images were captured for 2 minutes at 1 frame per second to record thermal bloom and dissipation in each individual sample. Thermal images were recorded and analysed via Radiometric Complete Online (Radiometric Infrared Solutions, 2011). Average temperature rise was used as the basis for analysis, as maximum temperature rise only corresponds to the hottest pixel measured. For all tests, the recorded frame corresponding to a measurement delay time of

45s was selected for comparison as this was the shortest common delay time across all samples tested for all treatment methods.

2.5 Calculating ore sortability performance

The sorting performance of each ore sample was determined by plotting ore sortability curves. These are analogous to the grade/mass recovery curves, used to assess the performance of flotation circuits. Metallurgical efficiency of a concentration process can be expressed by a curve showing the recovery attainable at any value of concentrate grade (Wills et al., 2006). In the case of electromagnetic ore sorting with infrared imaging (EM-IR), the concentrate grade is the grade of 'hot' fragments that have been accepted during sorting. An intrinsic sortability curve of an ore sample is determined by ordering fragments from highest to lowest copper grade. The cumulative grade (or cumulative copper recovery) can then be determined on a fragment by fragment basis (Tucker et al., 2013), and for different mass recoveries.

3 Comparing MW-IR and RF-IR sorting

3.1 The influence of processing method and presentation on fragment thermal response

Previous work (Batchelor et al., 2016) showed that for microwave sorting treatments, energy dose was the single most important variable for controlling the average temperature rise of fragments. In this work, the microwave or RF energy input has been kept constant for treatment each ore sample under equivalent conditions (between 0.7 and 1.0 kWh/t) to investigate whether there is improved selectivity in the heating of target minerals at radio frequency compared to microwave. The effects of processing method (microwave or RF) and fragment presentation (orientation 1 or 2, or rotating packed bed treatment with IR measurement in orientation 1) on average temperature rise under equivalent treatment conditions are illustrated for Ore 3, the quartz-monzonite sample, in Figure 4 (the results for all samples are shown in S1 in of the Supplementary Information). All treatments were performed at a target electromagnetic energy dose of 0.7kWh/t. For Ore 3, under microwave treatment conditions, the thermal response profile of the fragments is similar in both orientation 1 and orientation 2. The influence of fragment orientation in pilot scale microwave treatment was previously shown to have no adverse effect on sortability performance, as it did not make a hot fragment appear cold or vice versa (Batchelor et al., 2016). However, for RF monolayer treatments at equivalent dose, the average temperature rise for all fragments is higher. This is expected due to the uneven heating in the RF system for fragment tips closest to the electrodes, however these effects were observed to be more extreme in Ore 3 compared to other samples due to the increased angularity. The RF rotating packed bed treatments were undertaken to mitigate this effect. For Ore 3 and equivalent energy inputs, the thermal response profile is closer to that observed in microwave testing. The thermal responses of fragments in packed beds rather than monolayers will therefore be used for comparison with microwave treatments of ores for the remainder of this section.

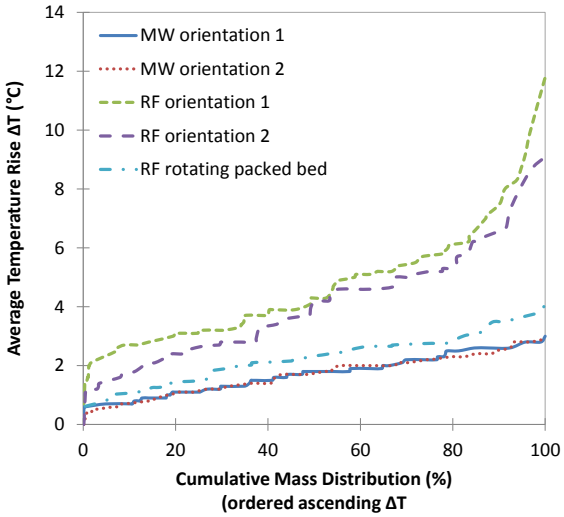

Figure 4: Ore 3 variation in ore thermal response profile due to fragment presentation method and frequency

The variation in fragment thermal response profiles for the five different ore samples tested are illustrated in Figure 5, for microwave orientation 1 and RF rotating packed bed treatments. The range of thermal responses observed is much greater for microwave treatment compared to RF treatment. With maximum individual fragment temperatures of over 30°C for microwave treatment, but only 12°C for RF rotating packed bed treatment. Given that treatments are carried out at equivalent energy dose, this suggests a difference in the selective heating of the different mineral phases between microwave treatment at 896 MHz and RF treatment at 27 MHz. Furthermore the relative order of the different ores varies, with Ore 2 exhibiting the highest average temperature rise in microwave and Ore 5 the highest in RF rotating packed bed.

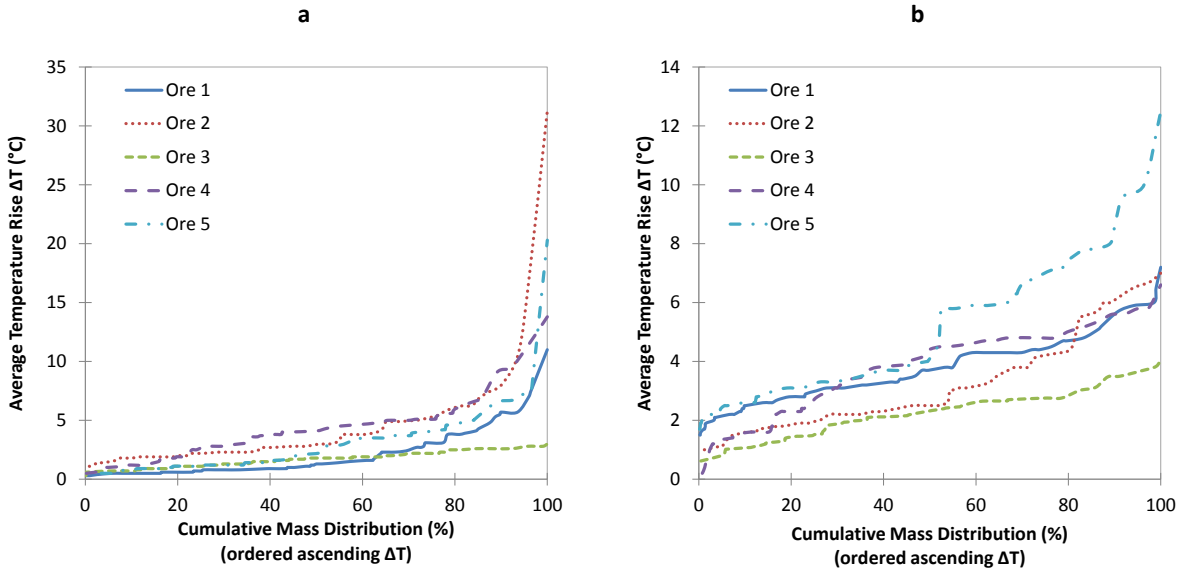

Figure 5: MW orientation 1 (a) and RF rotating packed bed (b) variation in thermal response profiles due to ore type

To further elucidate the difference between the behaviour of test fragments in microwave and RF processing, the comparative individual thermal responses for each fragment in each ore sample are illustrated in Figure 6. Interestingly, the fragments in Ore 3 exhibit very similar thermal responses under microwave and RF treatment conditions. For Ores 2, 4 and 5, the thermal response for the majority of fragments falls within a similar range under both microwave and RF conditions, typically in the range 5-10°C. However for Ore 1 there are a significant number of fragments that have an average temperature rise below 1°C under microwave conditions, but a temperature rise between 2 and 6°C in the RF. There are also a small number of fragments in Ores 2, 4 and 5 that exhibit a significantly higher temperature rise in microwave processing compared to RF. These large differences in the very hottest fragments suggest a difference in the selective heating of mineral phases within these ore fragments between microwave and radio frequencies, for example a difference in thermal response of the hydrated clay minerals and sulphide minerals. These different thermal responses will be considered in more detail in Section 3.2.

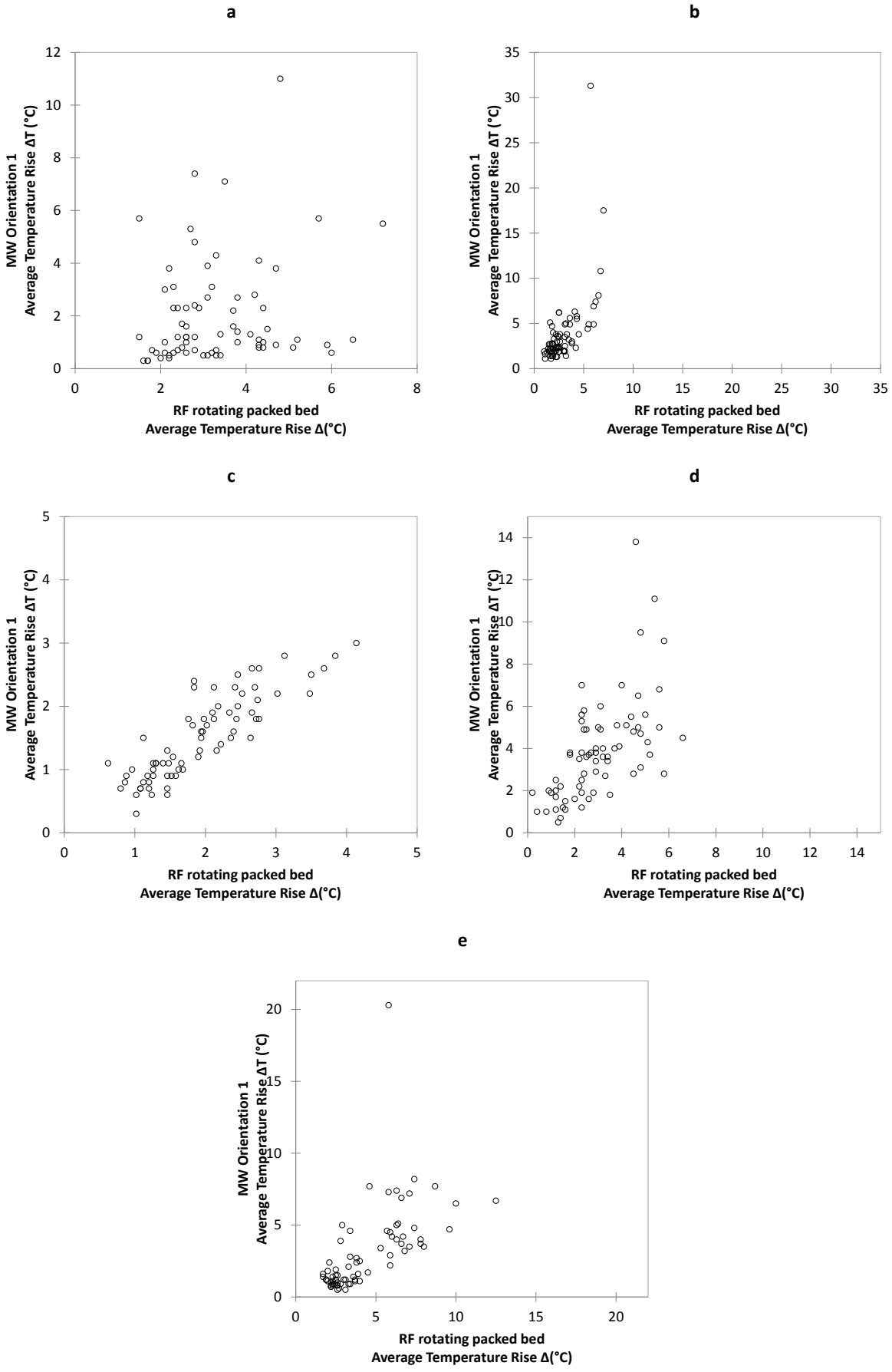

Figure 6 Ore 1 (a), Ore 2 (b), Ore 3 (c), Ore 4 (d) and Ore 5 (e) individual fragment thermal responses, RF rotating packed bed and MW orientation 1

3.2 Comparing MW and RF ore sortability

To determine whether radio frequency heating can provide a benefit over microwave heating for discrimination between valuable and uneconomic fragments, the sortability of the same fragments under equivalent conditions is compared. The metallurgical efficiency of any sorting process can be expressed as a curve showing the (copper) recovery attainable at any value of mass recovery. The intrinsic sortability of an ore sample is determined by ordering fragments from highest to lowest copper grade; cumulative recovery is then determined on a fragment by fragment basis (Tucker et al., 2013). The actual sorting performance is determined for both microwave and RF sorting by ordering the fragments according to individual fragment average temperature rise, from coldest to hottest. The closer the actual curves are to the intrinsic curve, the better the sorting performance.

S2 in the Supplementary Information illustrates the cumulative microwave and RF mass-copper sortability curves alongside the intrinsic mass-copper curves for each ore sample tested. Sortability performance can be readily determined from these curves by examining the copper recovery at different mass recoveries. Table 2 shows the intrinsic and actual microwave and RF rotating packed bed copper recoveries for each of the ores tested, at 25%, 50% and 70% mass recoveries (copper recovery values represent the recovery at the cumulative mass percentage for the fragments in each sample closest to the target mass recovery). Overall, the copper recovery is higher under microwave conditions compared to rotating packed bed conditions, for the majority of mass recoveries. It should be noted that whilst these arbitrary mass rejections are useful for comparing different ores, and different discrimination technologies, sorting considerations for real operations should be based on techno-economic considerations for a particular mine site. The optimisation of copper recovery by tailoring temperature cut points in MW-IR sorting is addressed in (Batchelor et al., 2016). The data presented here however indicates that there is no improvement in sortability performance using RF-rotating packed beds compared to microwave sorting.

Table 2 Intrinsic copper recoveries and actual microwave and RF rotating packed bed copper recoveries at 25%, 50% and 75% mass recoveries

		Copper Recovery %		
	Mass Recovery %	**Intrinsic**	**MW**	**RF**
Ore 1	**25**	49.3	25.9	29.1
	50	80.6	54.4	60.4
	75	94.0	91.2	76.4
Ore 2	**25**	53.0	36.0	29.9
	50	81.4	66.7	59.6
	75	96.1	86.2	85.4
Ore 3	**25**	64.0	12.5	9.7

	50	85.1	48.3	38.4
	75	94.0	65.2	64.5
Ore 4	**25**	59.5	38.1	46.9
	50	83.4	64.1	58.7
	75	95.6	90.5	87.5
Ore 5	**25**	62.2	27.8	14.1
	50	92.6	34.7	38.8
	75	98.8	79.8	73.9

Comparing selectivity in MW-IR and RF-IR sorting of ores

The differences in MW and RF sorting performance under equivalent conditions are most readily attributed to a change in the selectivity of heating different mineral phases within the ores. (Batchelor et al., 2016)showed that the main deviation from intrinsic sortability in microwave processing was due to the presence of iron sulphides and hydrated clays, which also heat well when exposed to microwave energy. The mineral conductivity measurements conducted by Genn and Morrison (2014) suggest a potential increase in conductivity and therefore heating rate at radio frequencies for sulphide minerals. It is therefore necessary to investigate whether changes in the relative heating of pyrite and chalcopyrite are responsible for lower copper recoveries in RF compared to microwave sorting.

To determine the influence of the three principle heated phases (chalcopyrite, pyrite and moisture) in the ores on the temperature rise of the fragments following microwave and RF treatment, multiple linear regressions were run for each of the five ores. The fragment heating results for microwave treatments in orientation 1 and orientation 2 were included as a single series to eliminate the effect of fragment orientation from the regression analysis. Table 3 presents the P-value outputs from the regression analysis. A P-value of less than 5E-02 (0.05*) is deemed to be statistically significant, whilst a value of less than 1E-03 (0.001**) is statistically highly significant.

Table 3 Multiple linear regression P-values for significance of heated phase content on the average surface temperature rise of fragments in ore samples following MW and RF rotating packed bed treatment. * significant, ** highly significant

	Ore 1		**Ore 2**		**Ore 3**		**Ore 4**		**Ore 5**	
	MW	RF	MW	RF	MW	RF	MW	RF	MW	RF
Chalcopyrite Weight%	$1.6x10^{-1}$	$6.9x10^{-1}$	$2.3x10^{-3}$*	$3.7x10^{-3}$*	$8.4x10^{-2}$	$5.3x10^{-1}$	$3.2x10^{-1}$	$1.7x10^{-1}$	$1.6x10^{-3}$*	$9.8x10^{-2}$
Pyrite Weight%	$4.6x10^{-3}$*	$8.5x10^{-1}$	$4.7x10^{-1}$	$4.4x10^{-2}$*	$9.8x10^{-1}$	$7.0x10^{-1}$	$1.1x10^{-2}$*	$3.1x10^{-2}$*	$1.6x10^{-5}$**	$9.9x10^{-1}$
Moisture Weight%	$4.8x10^{-1}$	$1.3x10^{-5}$**	$4.6x10^{-12}$**	$4.4x10^{-19}$**	$2.0x10^{-25}$**	$4.3x10^{-32}$**	$4.5x10^{-14}$**	$8.0x10^{-4}$**	$2.2x10^{-27}$**	$7.4x10^{-44}$**

For all the samples with the exception of Ore 3, either chalcopyrite or pyrite content was found to have a significant influence on individual fragment temperature rise in MW-IR sorting. It is noteworthy that the chalcopyrite influence was generally less statistically significant than the pyrite content in MW heating.

Interestingly, moisture content was highly significant in the microwave treatment of all ores except ore 1; in this case the large pyrite content was dominant. This potential threshold for MW-IR sorting based on the content of different heating minerals is elucidated later in Section 4.

A major observation from these P-values is that in RF rotating packed bed processing, moisture content is statistically highly significant for every single ore, and more so than for microwave processing, with the exception of Ore 4. This suggests an increase in the selective heating of moisture within clay minerals at 27 MHz compared to 896 MHz. This is exemplified in Figure 7 which illustrates the relationship between moisture content and individual fragment average temperature rise for microwave orientation 1 and RF rotating packed bed treatment at equivalent energy dose. As well as a tightening of the scatter in the trend between moisture content and temperature rise, there is an increase of between 20% and 30% in temperature rise for the hottest fragments in RF compared to microwave.

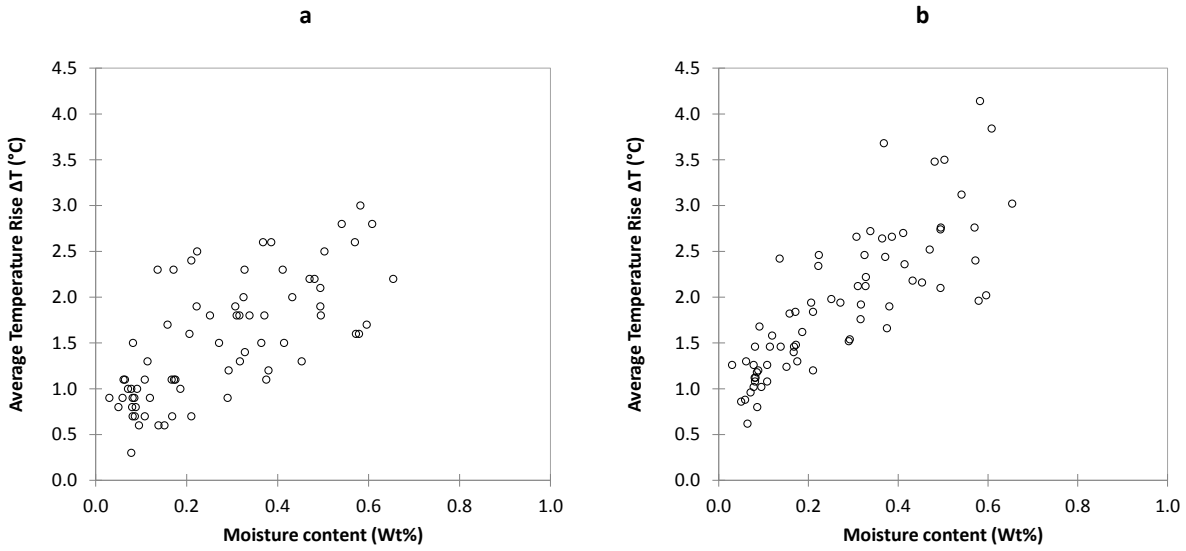

Figure 7 Ore 3 microwave orientation 1 (a) and RF rotating packed bed (b) individual fragment thermal responses versus moisture content

The P-values in Table 3 also show a clear reduction in the contribution of both pyrite and chalcopyrite to the heating of fragments during RF processing. It may be construed that there is a minor interaction between RF energy and sulphide minerals in Ore 2. However this can attributed to a degree of co-mineralisation between the sulphides and the hydrated minerals in some of the fragments; this is illustrated by the trends in Figure 8 which show the individual fragment total sulphide content versus moisture content for Ore 2 and Ore 3, and indicate a correlation between sulphide and moisture in Ore 2, but not in Ore 3.

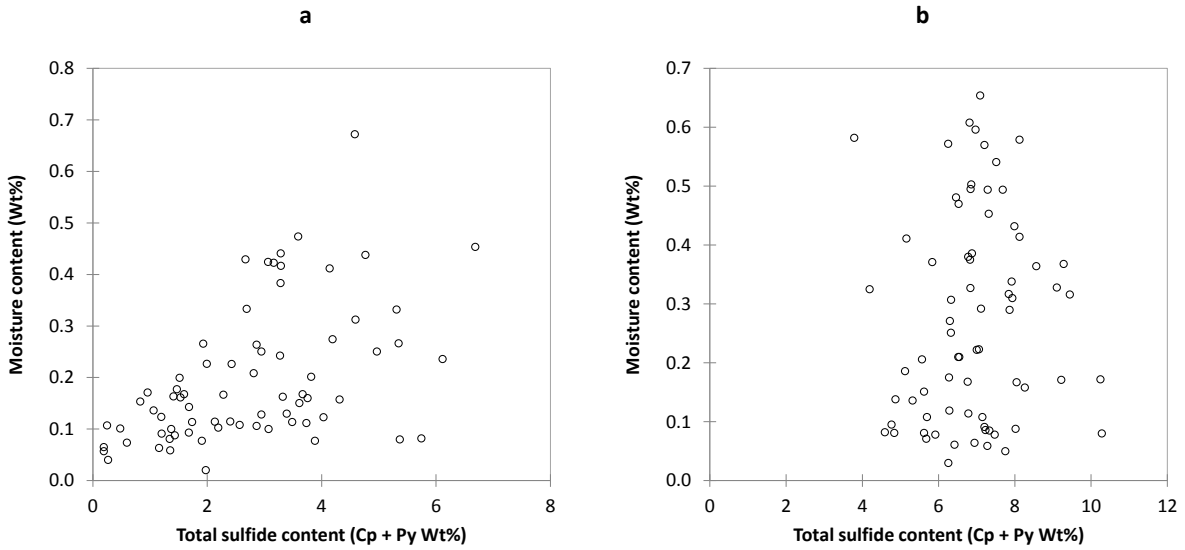

Figure 8 Ore 2 (a) and Ore 3 (b) individual fragment total sulphide mineral content (chalcopyrite + pyrite weight %) versus moisture content (weight %)

A full set of charts illustrating the relationship between temperature rise, sulphide content and moisture content for all five ores can be found in the Supplementary Information (S3-S7). Overall, these trends and P-values suggest that sulphide minerals do not interact at radio frequencies. The frequency dependence of electromagnetic properties is due to the relative contributions of different interaction mechanisms. However, dipolar rotation, ionic conduction and conductive losses all contribute to heating at both microwave and radio frequencies. Whilst differences in the relative contributions of these heating mechanisms are therefore expected, an absence of interaction at 27 MHz suggests another cause. A major difference between the RF and microwave systems is the absence of a significant magnetic field in the RF system; due to the parallel plate setup, the magnetic field is orders of magnitude smaller than the electric field. Therefore, any heating in RF is due predominantly to interaction with the electric field. It is proposed therefore that sulphide minerals in ores interact with the magnetic field at microwave frequencies. In figures S7-S11 in Supplementary Information, a small number of fragments exhibit a high increase in temperature in microwave processing that is not accounted for by either sulphide or moisture content. As these are not present in RF heating, it is possible that an unidentified heated phase interaction with the magnetic field is responsible. It was noted in (Batchelor et al., 2016) that a number of ore fragments tested contained weakly magnetic minerals such as

garnets, and strongly magnetic minerals such as magnetite. It is likely that these minerals, which due to their magnetic properties will interact strongly with magnetic fields, are the cause. This reinforces the need to understand the fundamental cause of these differences in selectivity between microwave and radio frequency.

4 Understanding selectivity using synthetic fragments

4.1 Synthetic fragment fabrication

To test the hypothesis that there is no significant interaction between sulphide minerals and electric fields in microwave and RF processing, synthetic fragments containing a single heated phase were produced. The synthetic particle transparent (non-heating) matrix was fabricated from polymethyl methacrylate (PMMA) and pulverised quartz using an adaptation of a method developed by Rizmanoski and Jokovic (2015) and previously used for validation of numerical modelling of ore fragment microwave heating (John et al., 2015). To produce a range of sulphide and clay contents, predetermined masses of -106+75 µm pyrite grains (purchased as lump pyrite from Gregory Bottley and Lloyd) or nominally -106 micron analytical grade montmorillonite powder were blended with the matrix mixture until homogenised. This even dissemination throughout the matrix minimised any heating effects due to texture. Thermogravimetric analysis of pure montmorillonite showed that the mineral contained 9.4%wt free water and 3.5%wt bound water, giving a total moisture content of 12.9%wt. Four fragments of each pyrite/montmorillonite grade were made to determine variations due to difference in electromagnetic field exposure in individual fragments of similar 'mineralogy'. A set of barren fragments (no pyrite or montmorillonite) was also produced to provide a baseline for comparison. The mixture for each set of 'identical' fragments was formed by hand into round fragments of approximately 30mm diameter, with an average mass of 25g. This rounded geometry allowed fragments to be treated as a monolayer in RF testing without significant shape effects observed in the RF monolayer heating of angular real ore fragments.

4.2 Synthetic fragment microwave and RF testing

Microwave treatment of synthetic fragments was conducted in a 2450 MHz multimode cavity and in the 27 MHz RF system, at an equivalent target dose of approximately 4 kWh/t. Although this dose is significantly higher than the economic 0.5-1.0 kWh/t target for EM energy dose in MW-IR sorting testing completed thus far, it was selected to allow any potential temperature rises of sulphides in the RF system to be distinguishable from background heating of the matrix.

For microwave testing, 8 fragments were placed around the edge of the plastic disc and placed under the thermal camera for cold imaging. The disc was then placed on the microwave turntable and heated the fragments treated for 5 seconds at 1.1kW applied power. Assuming all energy was absorbed, the comparative dose was approximately 4.4kWh/t across all tests. For 27 MHz RF monolayer testing, fragments

were placed in plastic trays on the conveyor belt. The samples were then treated at 5kW applied power for 20s giving an overall comparative dose of 4.3kWh/t across all tests.

4.3 Synthetic fragment results

Multiple linear regression analysis was run to determine the significance of microwave-heating phase content on the average surface temperature rise of synthetic fragments following batch monolayer microwave and RF treatment. Table 4 presents the P-value outputs from the regression analysis.

Table 4 Multiple linear regression P-values for significance of heated phase content on the average surface temperature rise of fragments in synthetic fragments following batch MW and RF monolayer treatment. * significant, ** highly significant

Synthetic fragments	Batch MW	RF Monolayer
Pyrite Weight%	$1.6x10^{-35}$ **	$1.1x10^{-01}$
Moisture Weight%	$2.7x10^{-45}$ **	$1.5x10^{-61}$**

As expected, both pyrite and moisture content have a statistically highly significant influence on the average temperature rise from microwave heating. However, there was no influence of pyrite content on temperature rise in RF heating. Figure 9 illustrates the individual synthetic fragment average temperature versus heated phase content following microwave and RF heating at equivalent energy dose of ~4.4kWh/t. The spread observed in the temperature rise of 'identical' fragments can be attributed to slight variations in fragment mass, shape, grade and absorbent phase distribution , all of which have previously been shown in previous work to have minor contributions to average temperature rise (John et al., 2015, Batchelor et al., 2016)

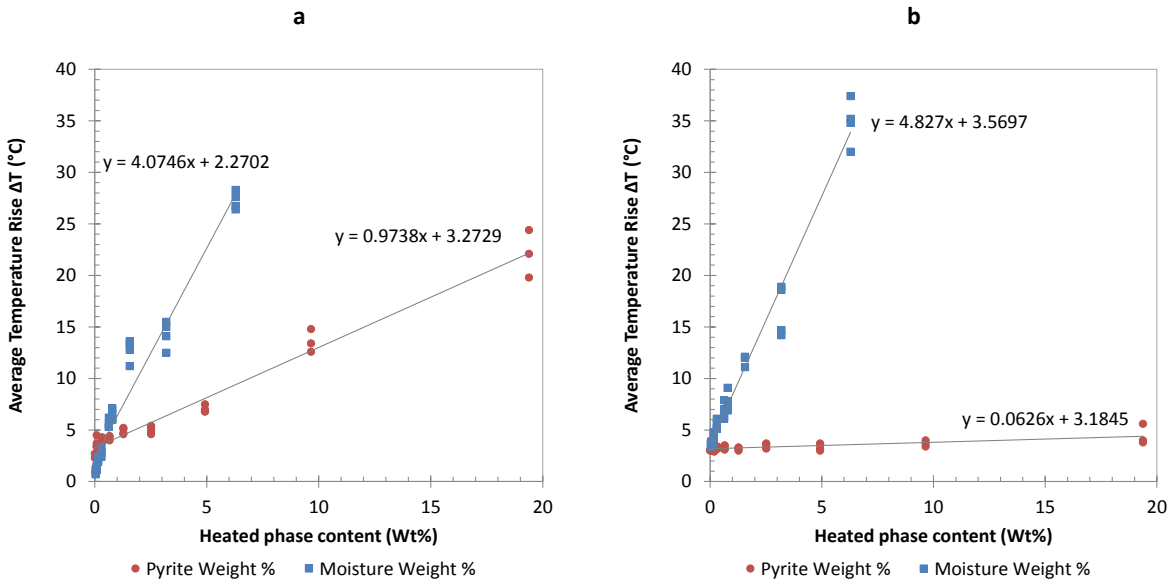

Figure 9 Microwave monolayer (a) and RF monolayer (b) individual pyrite and montmorillonite (moisture) containing synthetic fragment thermal responses, batch 4.3-4.4 kWh/t, and linear models

Applying the linear models in Figure 9a for the microwave heating of synthetic fragments with pyrite and moisture contents between 1 and 10 weight % indicates that at equivalent heated phase content the

temperature rise of the moisture (montmorillonite clay) containing fragments is 2.5 times that of pyrite containing fragments. Comparison of the linear models for temperature increase of montmorillonite containing synthetic fragments (again between 1 and 10 weight %) shows that for the same moisture content, the average increase in temperature is 25% higher in RF compared to microwave treatment. This again is an indication of increased selectivity in the heating of adsorbed interlayer water in the montmorillonite clay, as was seen in the heating of the real ore fragments. In RF heating, there is no discernible correlation between temperature rise and pyrite content. Furthermore, there is no significant temperature rise for the highest pyrite content fragments compared to the lower pyrite content fragments. This suggests that pyrite exhibits little or no heating in radio frequency systems at 27 MHz. This is a significant result and supports the proposal that semi conducting sulphide minerals heat in microwave systems via interaction with the magnetic field: in the RF system there is predominantly electric field between the RF electrodes. This explains why there were significant differences in the MW and RF heating profiles of low moisture-high sulphide fragments during testing of real ores.

The electromagnetic effects behind this type of behaviour in other conducting materials have been recently demonstrated by Porch et al. (2013). Generally, small conducting particles will heat rapidly when placed in a microwave field, limited only by the skin depth of the material (the depth at which the current density is equal to 1/e of the surface value (Meredith, 1998)). However, the internal electric field within these conducting particles is highly screened due to surface charges. Porch's investigation of the microwave absorption behaviour of small (non-magnetic) conducting particles showed that induction heating caused by eddy currents associated with the magnetic field is responsible for heating and was maximised at specific particle radii. For non-conducting and weakly-conducting particles, electric dipole induced heating is dominant, and maximised at specific conductivities relative to electromagnetic frequency. A summary of these limitations is shown in Table 5. A full derivation and background to these results are covered in detail in Porch et al. (2013).

Table 5 Electromagnetic heating factors and limitations for non-magnetic semi-conducting ore mineral particles, σ >0.1 S/m, particle radius 1nm <a< 1mm. Adapted from Porch et al. (2013)

Field	Microwave heating (f =2.45 GHz)	RF parallel plate heating (f =27.12 MHz)
Electric	Limited by screening. Maximum absorption when: $\sigma \approx \omega\varepsilon_0$	
Magnetic	Limited by skin depth: $\delta_s = \left(\frac{2}{\sigma\omega\mu_0}\right)^{0.5}$ Maximum absorption where: $a = 2.41\ \delta_s$	n/a minimal magnetic field present

Where δ_S = skin depth (m); σ = electrical conductivity of the material (S/m); f= frequency (Hz); ω = angular frequency (2πf rad/s); ε_0=permittivity of free space (8.854x10^{-12} F/m); μ_0 = permeability of free space (4π x10^{-7} m.kg/C^2).

Literature values for the conductivities of natural sulphide minerals such as pyrite and chalcopyrite have been reported between 1.0 and $1x10^5$ S/m (Pridmore and Shuey, 1976) with variations ascribed to differences in stoichiometry (Harvey, 1928, Parasnis, 1956) or the presence and concentration of impurities (Shuey, 1975). Given this range of values, it is perhaps not unexpected that these semi-conducting minerals could behave either closer to insulators or conductors depending on their (ore deposit specific) properties. Therefore, heating of semi-conducting minerals in RF at the grain sizes typically seen in porphyry copper ores can be extremely low, due to screening of the electric field and minimal magnetic field.

As well as elucidating how semi-conducting sulphide minerals may interact with electromagnetic fields during microwave processing applications, these results also highlight the threshold ratio of sulphides and clays required to provide even heating due to each mineral group at 2.45 GHz (assuming that all clays heat equally and all sulphides heat equally). Approximately 2.5 times the mass of sulphide to clay would result in equal temperature rises for fragments in which the microwave-heating minerals were evenly disseminated through the matrix. This understanding can aid in the selection of ores which could potentially be the most amenable to MW-IR sorting. Overall, low hydrated clay content ores with copper sulphides as the main sulphide, or with a high degree of co-mineralisation between copper and iron sulphides, present the best case for sorting at near intrinsic sortability using MW-IR. The application of RF-IR to sorting of mined materials has promise for applications where pure dielectric sorting is required (such as in the discrimination of high and low moisture materials) or where the conductivity of sulphide ore minerals is sufficiently low that electric field screening does not inhibit heating. To fully understand the amenability of any ore or material to MW-IR or RF-IR sorting, full characterisation of all heating phases and their relative weighted contributions to individual fragment heating is required in future test programmes.

5 Conclusions

Radio frequency heating followed by infra-red thermal imaging has been investigated as an excitation-discrimination technique for sorting of ores. By developing a novel presentation and bulk handling method to allow even heating of fragments within a pilot scale parallel plate RF system, the fragment-by-fragment thermal response of a number of ore samples and synthetic fragments has been evaluated and compared to microwave treatment at pilot and batch scales. It has been shown that there is an increase in the selectivity of the heating of hydrated clay minerals at RF compared to microwave frequencies. Significantly, it has been shown that heating of semi-conducting sulphide minerals at radio frequencies is limited by electric field screening. It is suggested that the interaction of these minerals at microwave frequencies is likely to be due to induction heating via eddy currents associated with the magnetic field component. Whilst RF-IR is not a viable technique for sorting of the porphyry copper ores tested here, it could find applications where sorting or grading of material based on moisture content is required. Thermal response profiles of synthetic fragments have shown that hydrated clay minerals heat approximately 2.5 times as much as sulphides at microwave frequencies for the minerals tested. Conductivity is suggested to be a key to determining the relative absorption of electric and magnetic fields and ultimately the heating response of semi-conducting minerals. The amenability of different ores and mine sites to both microwave and radio frequency IR sorting will be best determined in future through thorough characterisation of mineral electrical and magnetic properties, and via the development of statistical models that incorporate thermal response weighting of heated phase content, together with textural, geometric and process variables.

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