

Geophysical mapping of the occurrence of platinum group elements in the main sulphide zone of the Great Dyke in Zimbabwe

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ABSTRACT

This work sought to establish the geophysical signature of platinum group elements in a mineralized sulphide host rock. It has been established that complex resistivity of rocks depends on frequency. The variation of resistivity magnitude and phase for the samples were taken for frequencies in the range 10^{-2} to 10^2 Hz. In the first part, the mathematical relationship between resistivity amplitude and phase with frequency was obtained based on the Cole-Cole model equation. A MATLAB Code based on the direct inversion of the apparent resistivity spectrum was used to extract the “Cole-Cole” parameters. In the second part an experimental procedure to obtain the data was designed and a discussion of the results obtained was made. Overall, the results confirm the model to be a good candidate for use in mapping the occurrence of platinum group elements in sulphide zones. Its frequency dependency parameter c is the critical anomaly detection parameter. Several efforts to solve this problem by other geophysical methods failed to yield the desired or useable results. The reason was the complex and inverse nature of the problem. The practical method chosen from a host of geophysical methods was complex resistivity measurements based on the “Cole-Cole model”. The knowledge gap being bridged in this study involves the use of this method to detect the base of the main sulphide zone.

1. Introduction

An understanding of physical properties of rocks from mining and exploration are crucial in the interpretation and planning of geophysical surveys (Van Schoor, Marè, and Fourie, 2009). Spectral induced polarization is one of the subtle methods for prospecting and solving geological problems mostly for deposits of infection type where host rock undergo negligible change in resistivity (Zhang et al. n.d.). The main aim of this work was to come up with a geophysical method that locate the base of the main sulphide zone (MSZ) and coincidentally the platinum peak on sample core or in situ on the mining underground reef. The scope of the problem is as depicted in Fig. 1 below showing the vertical distribution of platinum and other platinum group elements in the Great Dyke of Zimbabwe. The so-called peak of the platinum group elements or base of the main sulphide zone is as shown by the maximum height of 4000 ppb on the graph (Oberthür et al., 2013). What is shown on the graph as the horizontal variable; distance in metres, is in fact vertical distance on the reef wall. The percentage abundance of the platinum group elements is then shown as the vertical variable on the

graph in parts per million or billion (ppm/ppb) so it is this vertical position corresponding to the platinum peak which is the core of this assignment. There are several subsidiary peaks due to other elements like palladium, gold, copper and nickel partly to the left and also to the right but of primary concern is the platinum peak. The mineralogical distribution shown is consistent throughout the Great Dyke. This main platinum peak is the most crucial and sought-after reference position for economic mining and its location is a prerequisite before blasting can be done. Core at the yard and in situ is subjected to lithological and geotechnical logging by experienced Zimplats geological personnel. This involves careful examination of lithology, texture, structure, alterations etc. (www.Zimplats.com). The current approach is to detect this zone is through the visual inspection method which require a careful look and inspection of the position where the rock texture of the sulphides visibly changes from coarse to fine (www.Zimplats.com). This marks the base or relative zero position. The challenge is to find a geophysical method that can replace this relatively subject procedure of determining the zero position. In this study the complex resistivity method was put to test for suitability of being engaged. If successful and confirmed as shown by the

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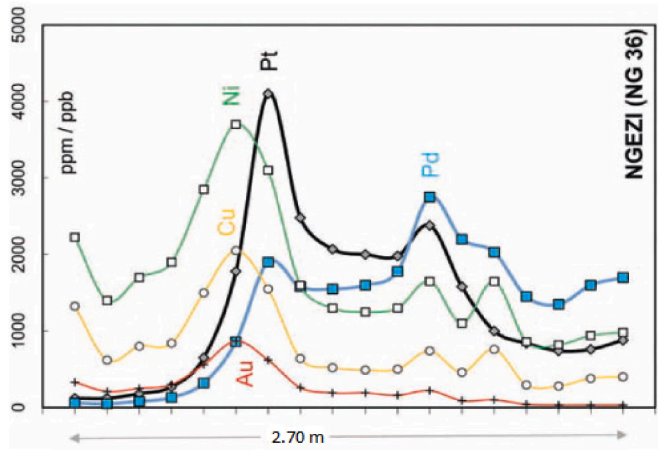


Fig. 1. Geochemical profile of the percentage abundance of platinum group elements in the Great Dyke for Ngezi.

experimental results when used in situ this base is to be continuously marked by repeating the same procedure while connecting a line on the reef wall that will map the MSZ base to serve as a blasting guide in the mining process.

The solution to the research question has implications to the way mining is done in the mineralized segment of the Great Dyke and possibly regionally and international appeal in establishing a platinum signature in exploration. In low sulphides platinum group elements induced polarization is an effective tool for mapping the disseminated sulphides and estimating host rock resistivity (Stephen J. Balch). Hence reference is often made to the potential of complex resistivity to achieve this objective. Also of interest in this research is some unpublished work done by others in theory and in practice to try and find solution to this fairly standard geophysical problem. The unique contribution has been the repeated application of the inversion algorithm to small sub-samples to generate a useable trend from the Cole-Cole parameters. The methodology and conclusion remain available for further test.

1.1. Relevant setting

Fig. 1 shows the geochemical profile of a typical core sample NG 36 for some selected elements (Cu and Ni in ppm and Pt, Pd and Au in ppb) across the main sulphide zone at Ngezi showing various zones (Moon and Khan, 1994). Fig. 2, show its geographical location physically in the



Fig. 2. The geographical setting of source samples, Ngezi platinum mine and its location in the Zimbabwe's Great Dyke.

whole Great Dyke in particular and Zimbabwe in general. Also shown in Fig. 2 are other mines engaged in similar mining operations in the same geological setting.

2. Theoretical considerations

It has been observed experimentally that the effective conductivity of a rock for alternating current is both variable and complex. Impedance is a complex function whose value at very low frequency is due to the effective change in conductivity of the medium. This is an effect that is extremely well pronounced in sulphides (Lou and Zhang, 1998). The main reason for this is that the applied current sets up a voltage across the various interfaces between inhomogeneities in the medium. This voltage is in general not in phase with applied current and its amplitude is a complex function of frequency. Electric currents may be propagated in rocks in three ways: electronic, electrolytic and dielectric (Properties n.d.). Most rocks' mode of conduction is electrolytic where charge carriers in the pore fluid are ions. The rest of the matrix of the solid grains are semi-conductors except conducting clay minerals at the surface as well as metallic grains (Society n.d.). The induced polarization method is effectively and extensively used for base metal as well as locating grades of minerals that are low such as disseminated sulphides (Moon and Khan, 1994). Contact between electrolyte and rock or mineral particles produces polarization potential that accounts for measured resistivity and phase values in complex resistivity. Frequency dependency characteristics are studied using spectral induced polarization. The "Cole-Cole model" is a formulae that describes the spectrum of complex resistivity (Zhang et al. n.d.). The "Cole-Cole model" is often the basis of understanding and interpreting induced polarization data (Jianping Xiang et al., 2003). The complex impedance data is inverted using an iterative computer program (Jianping Xiang et al., 2003). The "Cole-Cole model" has been proven to be valid for describing IP complex resistivity effects in mineralized samples theoretically (Lou and Zhang, 1998).

2.1. The Cole-Cole model

The basic formulation for the "Cole-Cole model" is based on the following relation (equation (1)):

$$\rho(\omega) = \rho_0 \left[1 - m \left(1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right] \tag{1}$$

Complex resistivity amplitude $\rho(\omega)$ is a function of angular frequency (ω) and the parameters are resistivity at zero frequency (ρ_0), chargeability (m), time constant (τ) and the frequency dependency (c).

$$\begin{aligned} \text{From formula (1): } (i\omega\tau)^c &= (\omega\tau)^c e^{i(4n+1)\frac{\pi}{2}c} \\ &= (\omega\tau)^c \left[\cos(4n+1)\frac{\pi}{2}c + i \sin(4n+1)\frac{\pi}{2}c \right] \\ &= R - 1 + iI \end{aligned} \tag{2}$$

$$\text{where : } R = 1 + (\omega\tau)^c \left[\cos(4n+1)\frac{\pi}{2}c \right] \text{ and } I = (\omega\tau)^c \left[\sin(4n+1)\frac{\pi}{2}c \right] \tag{3}$$

For ($n = 0$), R and I can be represented by (4)

$$R = 1 + (\omega\tau)^c \cos\left(\frac{\pi}{2}c\right) \text{ and } I = (\omega\tau)^c \sin\left(\frac{\pi}{2}c\right) \tag{4}$$

Putting equation (2) into (1):

$$\begin{aligned} \rho(\omega) &= \rho_0 \left[1 - m \left(1 - \frac{1}{R + iI} \right) \right] \\ &= \rho_0 \left[1 - m \left(1 - \frac{R - iI}{R^2 + I^2} \right) \right] \end{aligned}$$

$$= \rho_0 \left[1 - m + \frac{mR}{R^2 + I^2} - i \frac{mI}{R^2 + I^2} \right] \quad (5)$$

From equation (5), it is clear that complex resistivity amplitude (A) is a combination of the real (Re) and the imaginary (Im) components and the phase (φ) (Zhang et al. n.d.)

$$A = (Re^2 + Im^2)^{\frac{1}{2}} \text{ and } \varphi = \arctan \left(\frac{Im}{Re} \right)$$

2.2. The direct inversion algorithm

Direct inversion is a way of determining the parameters in the equation and form the basic framework of the method. The ‘‘Cole-Cole’’ equation (1) can be directly inverted i.e., from a set of experimental data be used to produce estimates of ρ_0, m, τ and c . A detailed step by step derivation of the direct inversion of the parameters is contained in (J. Xiang et al., 2001). Summarized below are the main steps in the estimation method.

1. Estimate of $\tau(c)$:

$$A_k = \frac{\cos\left(\frac{c\pi}{2}\right) \omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c}$$

$$C_k = \frac{\sin\left(\frac{c\pi}{2}\right) \omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c}$$

$$D_k = \frac{\omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} \quad (6)$$

$$\text{and } B_k = R_k - D_k \quad k = 1, \dots, N \quad (7)$$

$$\tau^c = X = \frac{\sum_{k=1}^N (A_k B_k + I_k C_k)}{\sum_{k=1}^N (A_k^2 + C_k^2)} \quad (8)$$

$$\text{From equation (1)} \quad \frac{\omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} = \frac{\rho_0 - \rho_{k+1}}{\rho_{k+1} - \rho_k} = R_k + I_k \quad [5] \quad (9)$$

In this case R_k and I_k are the real and imaginary parts of Z_k respectively $Z_k = R_k + I_k$ and $k = 1, \dots, N$.

2. Approximation of ρ_0

Computation of parameters $\mu_k, \lambda_k, \varnothing_k$ and φ_k

From equation (9) $\rho_0 = R_o + I_o$ and

$$\frac{1}{\rho_{k+1} - \rho_0} = \mu_k + i\lambda_k \text{ while } \frac{\rho_{k+1}}{\rho_{k+1} - \rho_k} = \varnothing_k + i\varphi_k \quad (10)$$

where μ_k and \varnothing_k are real parts while λ_k and φ_k are imaginary parts of the expressions given.

$$R_k = \mu_k R_o - I_o - \varnothing_k \quad (11)$$

$$I_k = \mu_k R_o + I_o - \varphi_k \quad (12)$$

Substituting equations (11) and (12) into equation (8) provides

$$X = PR_o + I_o - H \quad (13)$$

where P, Q and H are intermediate variables. These Intermediate variables enable us to calculate compound parameter $\tau^c = X$.

$$P = \frac{\sum_{k=1}^N \frac{\omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} \left[\cos\left(\frac{c\pi}{2}\right) \mu_k + \sin\left(\frac{c\pi}{2}\right) \lambda_k \right]}{\sum_{k=1}^N \left(\frac{\omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} \right)^2} \quad (14)$$

$$H = \frac{\sum_{k=1}^N \frac{\omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} \left[\cos\left(\frac{c\pi}{2}\right) \varnothing_k + \sin\left(\frac{c\pi}{2}\right) \varphi_k + \left[\cos\left(\frac{c\pi}{2}\right) \left(\frac{\omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} \right) \right]}{\sum_{k=1}^N \left(\frac{\omega_k^c \omega_{k+1}^c}{\omega_k^c - \omega_{k+1}^c} \right)^2} \quad (15)$$

$$M(c) = \begin{pmatrix} A_k P - \mu_k \\ C_k P - \lambda_k \end{pmatrix} k = 1, \dots, N \quad (16)$$

C_k in this case is as defined in equation (6) while c below is the frequency dependance parameter.

$$L(c) = \begin{pmatrix} A_k H - \varnothing_k - D_k \\ C_k H - \varphi_k \end{pmatrix} k = 1, \dots, N \quad (17)$$

The multifold least-squares estimation gives

$$\rho_0 = [M^T(c)M(c)]^{-1} M^T(c)L(c) \quad (18)$$

3. Estimation of $m(c)$

$$m(c) = \frac{\sum_{k=1}^{N+1} \left| \frac{(i\omega\tau)^c}{1+(i\omega\tau)^c} \right| \left| \frac{\rho_0 - \rho_k}{\rho_0} \right|}{\sum_{k=1}^{N+1} \left| \frac{(i\omega\tau)^c}{1+(i\omega\tau)^c} \right|^2} \quad (19)$$

With this set of parameters, ‘‘Cole-Cole model’’ and a set of estimated data, depending on the choice of c which is obtained as $\rho_c(\omega_k)$. The optimal value of c is found by minimizing the total square error using the golden search algorithm.

$$S(c) = \sum_{k=1}^{N+1} (\rho_k - \rho(\omega_k))^2 \quad (20)$$

To determine the ‘‘Cole-Cole model’’ four parameters, resistivity amplitude (ρ_0), chargeability (m), time constant (τ) and frequency dependency (c), must be estimated. The resulting expressions from the direct inversion method are useful in writing the MATLAB Code needed to estimate the ‘‘Cole-Cole’’ parameters, pivotal in interpretation of this geophysical survey.

Equation (1) can be expressed as a complex number consisting of the real and imaginary components (Zhang et al. n.d.). The phase is the inverse tangent of the complex part divided by the real part. These two important parameters, resistivity amplitude and phase, can thus be inferred and are measurable in the field and in the laboratory.

3. Materials and methods

The experimental research follows the set up presented in (Jaggard and Fell, 1988). Spectral induced polarization measurements in the frequency domain are comprised of electrical impedance (Z) measurements on a core or block of predetermined length and cross-sectional area. This is done at different frequencies over a frequency spectrum from 10^{-2} to 10^2 Hz. The impedance data may be represented in resistivity amplitude and phase form as real and imaginary components (Jaggard and Fell, 1988). The method employs spectral induced polarization (SIP) in the frequency domain. The instrument used was the spectral induced polarization (SIP) Fuchs III. It is used for both direct and precise ac resistivity measurements. An SIP Fuchs III made by Radic Research was used to obtain values of resistivity amplitude and phase as predicted from equation (5).

Drilled core samples were cut in the laboratory into small semi-circles of about 2 cm. An SIP Fuchs III meter was then used to induce current into the laboratory samples. From the resulting potential difference and current, values of resistivity amplitude and phase for 19 frequency values per each sample were collected. The point where copper sulphides visibly changed from coarse to fine was identified as the base and zero position. Calibration using a ruler marking positions

above as positive while those below as negative gave relative positions shown as x. This relative position for each sample as determined from visual inspection was noted. Thus, for each sample the variables sought were relative position, frequency, resistivity amplitude, and phase. The results are shown in supplementary material A. Values of resistivity amplitude and phase were separately plotted against relative position and a correlation was made. The graphs are shown in supplementary material B.

A MATLAB Code (Supplementary material C) developed from equations for the direct inversion of the Cole-Cole equation was used to estimate the parameters for specific value of frequency, resistivity amplitude and phase for each value of the variable position. The source code is publicly available on the IAMG server (Jianping Xiang et al., 2003). The resulting values of the parameters were then plotted against the vertical variable position to investigate the presence of any correlation and useable pattern.

Values of resistivity amplitude and phase were obtained from laboratory measurements of small cut semi-circular pieces of rock samples of lengths about 0.2 m. The variation of magnitude and phase for the samples were obtained for frequencies in the range 10^{-2} to 10^2 Hz. This was done on a sample whose code is MLED21.

4. Results

Results of the values of resistivity amplitude and phase as a function of frequency for each position variable are available in supplementary material A. Plots of resistivity amplitude versus position are also presented in supplementary material B. The values of resistivity amplitude and phase in supplementary material A were used to plot the graphs in supplementary material B. The MATLAB code in supplementary material C was used to generate the “Cole-Cole” parameters for each relative position and the values are in Table 1. These values of the “Cole-Cole” parameters were then used to make the plots of each of the parameters versus position for purposes of establishing whether or not there exist any useable correlation at the base of the main sulphide zone.

Presented in Table 1 are the results for variation of the frequency dependency c from equation (1) as a function of position. In the sample,

Table 1
Values of Cole-Cole parameters as a function of position for MLED21.

Position (x)	Frequency Dependence (c)	Resistivity amplitude (ρ) (E+04)	Time constant (τ)	Chargeability (m)
-1.7	0.097	2.36	0	0.015
-1.6	0.6214	2.02	7.27E-14	6.09E+04
-1.5	0.0012	2.98E-02	0	1.71E-04
-1.4	0.0042	1.24E-08	0	8.14E-04
-1.1	0.1006	1.25	0	0.0234
-1.0	0.5182	2.87	2.79E-07	4.8386
-0.9	0.0974	1.87	0	0.0329
-0.3	0.5559	2.52	3.94E-07	4.5198
-0.25	0.5002	2.12	7.90E-08	7.5772
-0.2	0.5898	2.30	2.25E-07	6.4412
-0.1	0.5605	2.43	1.15E-06	2.8633
-0.01	0.5002	2.69	3.24E-07	4.2053
0.0	0.6998	1.88	4.58E-07	5.1436
0.2	0.476	1.56	2.63E-6	6.154
0.25	0.5741	4.16	3.43E-06	1.9544
0.3	0.5305	3.36	6.80E-07	3.4398
0.5	0.6649	1.62	7.86E-12	5.75E+03
0.6	0.5784	2.62	1.73E-07	7.1852
0.8	0.5852	2.08	7.18E-13	9.04E+03
0.9	0.5022	2.62	2.62E-07	4.7346
0.95	0.6044	2.62	2.97E-07	5.8227
1.0	0.0715	1.41	0.00E+00	0.0202
1.1	0.518	2.18	2.47E-10	152.3935
1.2	0.0012	1.23	0.00E+00	2.45E-04
1.3	0.5932	2.47	3.63E-07	5.1306
1.4	0.5549	5.549E-03	5.56E-09	38.777

MLED21 (sample core identity) a full profile from -1.7 m to 1.4 m was selected. For the purposes of this study, a longer range (full channel) was chosen but in practice, normally in the mining operations the required band is about -0.5 m-0.5 m. Fig. 3 shows the graph of frequency dependency c against position (x) for MLED21.

5. Discussion

In this study, an effort was made to establish a useable correlation between relative position and any of the measurable variables obtained from spectral induced polarization. It must be recognized that this has been a subtle problem which have evaded solution from conventional approaches like using standard geophysics approaches of using magnetic susceptibility or electrical resistivity. Spectral induced polarization was then put to test for suitability. The results of the research were studied from two points of view. First an analysis of usability of the plots from resistivity amplitude and phase separately as a function of the relative position was performed. The plots are shown in supplementary material B. The graphs did not yield any useable trend. On this basis, they were of no use in the present study. In addition, the correlation between the “Cole-Cole” parameters and the relative position was subjected to a separate analysis.

The plots for resistivity amplitude and resistivity phase did not produce any anomaly or useable trend at and around the base of the main sulphide zone. Efforts to estimate “Cole-Cole” parameters by any method like curve fitting also did not yield useful results. Rather, the direct inversion algorithm (J. Xiang et al., 2001) method employing the MATLAB Code was used to estimate the “Cole-Cole” parameters. Attention was then given to the “Cole-Cole” parameters. After the inversion, each of the parameters were plotted as a function of relative position. Resistivity amplitude and chargeability yielded random uncorrelated variation hence their graphs have been excluded in this research. The frequency dependency c, is an important parameter in spectral induced polarization that can detect orebodies within the mineralized host rock and can discriminate polarizable bodies (Lou and Zhang, 1998). The time constant gave the biggest variance and response. However, it did not produce a useable trend.

It was the frequency dependency parameter c, that generated encouraging and reassuring pattern as shown in Fig. 3. From literature, the frequency dependence was obtained to be 0.5-1.0 at peak for volume and surface polarization with uniform grains. Around the base of the main sulphide zone, the frequency dependence fluctuates with an average between 0.4 and 0.65 with the peak at the base of the main sulphide zone. The maximum value of c = 0.7 coincides with the platinum peak. Fig. 1 shows the spatial distribution of platinum group elements whose average resistivity magnitude contributes to the overall value being measured. There are several peaks and subsidiary peaks from the various elements occurring together with platinum.

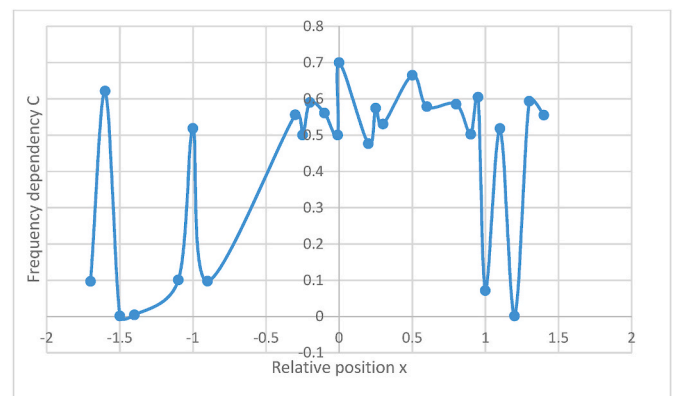


Fig. 3. Graph of frequency dependency c against position (x) for MLED21.

This is no coincidence; it is indeed the discriminating parameter. This can be marked on the sample core or in situ on the wall. Repeating the procedure maps a line on the reef wall which marks the crucial blasting reference guide.

6. Conclusions

Graphs of resistivity amplitude and phase versus position in the supplementary material A failed to produce a useable pattern that can be used to detect and delineate the position of the main sulphide zone. However, extraction of Cole-Cole parameters and a plot of the frequency dependency parameter c versus relative position produced interesting results. The resistivity at zero frequency ρ_0 and chargeability m produced haphazard and uncorrelated pattern that have little prospect of usability. The time constant τ and the frequency dependency c , gave interesting correlations which is consistent with theoretical predictions (Lou and Zhang, 1998). Time constants may require more samples to establish its exact correlation but it has the largest response. The frequency dependence gave a simple and useable and to convincing degree of accuracy excellent peak at the platinum group element peak.

In this research, it is hereby concluded that the peak of the frequency dependency c , on the Cole-Cole equation has something strong to say regarding the position of the platinum group element peak. Its value was found to be about 0.7 at the platinum peak. It is no coincidence that they reach the peak at the same time, it is indeed the discriminating and anomaly detecting parameter. According to the generalized theoretical conclusions from many experimental data, the frequency dependence c was found to be 0.5–1.0 for surface and volume polarization with uniform grains (Lou and Zhang, 1998). The experimentally obtained value of the frequency dependence c of 0.7 is well within the published and accepted theoretical range. It is against this basis that the complex resistivity method is presented as a valid candidate for solving the research question.

Contribution of authors

Conception and design were performed by [B. Siachingoma, Dr. Hlatywayo and Dr V. Midzi]. Material preparation and data collection by [B.Siachingoma and Dr L.P. Mare]. All authors commented and corrected previous versions of the manuscript. We are also grateful to the anonymous reviewers and the editor for their valuable comments,

input and provisions for corrections.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafrearsci.2023.104857>.

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