Liberation of Emeralds from Micaceous Host Rock Using Electric-Pulse Disaggregation Versus Conventional Processing

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ABSTRACT: In ore processing, electric-pulse disaggregation (EPD) is used for the liberation of mineral crystals from host rocks. Since 2019, EPD technology has been used exclusively to recover emeralds produced from the Kagem mine in Zambia. This article compares the differences in the recovery of emeralds from micaceous schist host rock at the Kagem mine by EPD technology versus the conventional hand-cobbing method. The amount of emeralds obtained using both methods was similar, but EPD had numerous advantages in terms of liberation speed, ease of performing the process and the characteristics of the liberated emeralds.

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Figure 1: Emerald crystals are recovered from micaceous host rocks at the Kagem mine in Zambia. The gems must be extracted from the micaceous material prior to sorting and quality assessment. Photo © Gemfields Ltd, 2021.

Figure 2: Kagem is considered the world's largest emerald mining area. This photo shows one of the currently active pits. Photo © Gemfields Ltd, 2021.

In the gem industry, the size and quality of rough material play a crucial role in its pricing. Thus, one of the primary goals during mining and recovery is the liberation of the rough stones without any breakage that reduces their size or diminishes transparency. This is particularly important for gem material that is 'frozen' within host rock rather than crystallising in open cavities or 'pockets'. An excellent example of this is provided by emeralds that form in schist-type deposits (e.g. Figure 1) and must be liberated from their host rock before they can be sorted and cut into gemstones.

Electric-pulse disaggregation (EPD) is a mineral-processing technology developed as an alternative to mechanical crushing to liberate mineral grains and crystals from any rock type, regardless of its lithology or grain-size distribution (Cabri *et al*. 2008). Additional terms for this technique include *electrical fragmentation, electrical disintegration, high-voltage pulsed-power fragmentation* and *high-voltage breakage* (or *high-voltage pulse breakage*). EPD technology replaces the compressive force used for mechanical crushing with tension caused by the shearing effect of a localised explosion. During the EPD process, rock material is immersed in a water bath, where it undergoes fragmentation when subjected to high-voltage pulses that are greater than 50 kV. The high voltage causes the rock to break along zones of weakness, usually represented by grain boundaries. As a result, mineral crystals are mostly liberated in their original sizes and shapes (Andres 1995; Cabri *et al*. 2008; van der Wielen *et al*. 2014). In addition, the EPD technique can be used to 'pre-weaken' ores before conventional processing (Wang *et al*. 2011).

In this study, we focus on emerald liberation using the EPD Spark-2 device installed at the Kagem mine in Zambia (Figure 2), in comparison to the conventional hand-cobbing approach. The use of EPD Spark-2 equipment to process different types of geological samples for the extraction of gems, diamonds, and precious and rare metals was reviewed by Cabri *et al*. (2008) and Rudashevsky *et al*. (2018). This study specifically explores the effectiveness of this device for liberating emerald grains greater than 2.8 mm in size from their micaceous matrix and compares the performance of this technique to conventional mechanical hand cobbing that is more commonly used for the recovery of gem material at similar deposits.

BACKGROUND

Use of EPD in Geoscience and Gem Applications

An extensive database of peer-reviewed publications on different applications of EPD in geosciences is available at www.mineralogy.online, and various studies have revealed its applications and advantages as compared to mechanical crushing for the comminution of ores

(Lastra *et al*. 2003; Ito *et al*. 2009; Matko 2020) and the recovery of gem materials (Rudashevsky *et al*. 2018). EPD is used in process mineralogy (analysis of relationships between ore and gangue or accessory minerals in order to optimise the recovery of target elements), mineral processing (treating ores and mineral products in order to separate the valuable minerals from the gangue) and as a sample preparation technique for:

- Extraction of grains of precious metals such as Ag, Au and platinum-group metals from ore material (Cabri *et al*. 2008; Rudashevsky *et al*. 2018)
- Extraction and concentration of diamond-indicator minerals, microdiamonds and various accessory minerals from kimberlite and other matrix rocks (Cabri *et al*. 2008; Rudashevsky *et al*. 2018; Matko 2020)
- Recovery of gem rough from host rock as undamaged crystals (Cabri *et al*. 2008; Rudashevsky *et al*. 2018)
- Recovery of fossils and microfossils from rocks (Saini-Eidukat & Weiblen 1996; Beasley *et al*. 2020)

Some specific gem applications of EPD technology include recovering emeralds at the Sandawana mine in Zimbabwe and diamonds elsewhere in Zimbabwe (Andres 1995). The EPD Spark-2 device, in particular, has been used at the Korkodino demantoid mine (Cabri *et al*. 2008), and it is presently employed at the Poldnevskoy demantoid mine in Russia. In addition, since 2019 the EPD Spark-2 device has been used at the Kagem emerald mine in Zambia.

Kagem Emerald Mine

The Kagem emerald mine (Figure 2) is operated by Gemfields Ltd, one of the world's leading suppliers of coloured stones. Kagem emeralds most commonly occur in micaceous rocks adjacent to quartz veins and pegmatites that caused hydrothermal alteration of the talc-chlorite-tremolite-magnetite schist host rocks (Zwaan *et al*. 2005; Cook 2009).

Gemfields acquired the Kagem mine in 2008, in partnership with the Zambian government through the Industrial Development Corporation, and has provided a steady supply of emeralds to the gem trade. Today, the Kagem mine produces about one-third of the world's emeralds by volume and is reportedly the world's largest producing emerald mine, covering 41 km^2. The Kagem mine aims to positively impact local communities, in alignment with the United Nations' Division for Sustainable Development Goals (see https://sdgs.un.org/goals). In addition, Kagem provides funds for conservation initiatives aimed at protecting Africa's wildlife.

EPD Technology at the Kagem Mine

The EPD Spark-2 device at the Kagem mine (Figure 3) was developed by CNT Instruments LLC (St Petersburg, Russia) and is housed in a separate facility beside the sorting house. The equipment includes a 2.5 × 2.5 × 2.5 m Faraday cage and separate high-voltage grounding. A specially designed power supply and control board are connected to a Marx generator, which consists of ten impulse capacitors connected in parallel to allow the build-up of high voltage that can exceed 250 kV. An array of spark gaps (spherical electrodes separated by an adjusted distance) is triggered in the air, closing the circuit so that the discharge occurs in a series arrangement. The inductance coils in the circuit regulate the timing of the discharges. Due to a sudden increase of electric current in the expanding discharge channel filled by high-density plasma, a physical tensile force is exerted on the rock, resulting in its explosive breakdown below the electrode inside the water-filled chamber (Figure 4; see also Andres 1995; Cabri *et al*. 2008).

MATERIALS AND METHODS

Samples of emerald-bearing micaceous schist from Kagem's run-of-mine product were used for this study. They were pre-tumbled to remove some of the mica and other easily detachable gangue and to provide roughly equivalent-sized pieces for the experiments. Two batches were prepared to yield a similar composition, quality and quantity (Figure 5) to test emerald extraction using EPD vs conventional hand cobbing:

- Batch 1 (for EPD): 26 pieces with a total weight of 755.0 g and an average mass of 29.0 g/piece
- Batch 2 (hand cobbing): 21 pieces with a total weight of 750.0 g and an average mass of 35.7 g/piece

The procedures used for each processing technique are described below and summarised in Figure 6. The following were noted individually for each batch:

- Weight of the material produced
- Characteristics of the material produced
- Amount of time taken
- Ease of performing the process

Batch 1 was processed by the EPD Spark-2 device using a 16 mm sieve for 1 minute at 1 Hz frequency with a 25 mm distance between the electrode and the sieve (again, see Figure 4), using an output voltage of over 250 kV in a 40 L chamber filled with tap water.

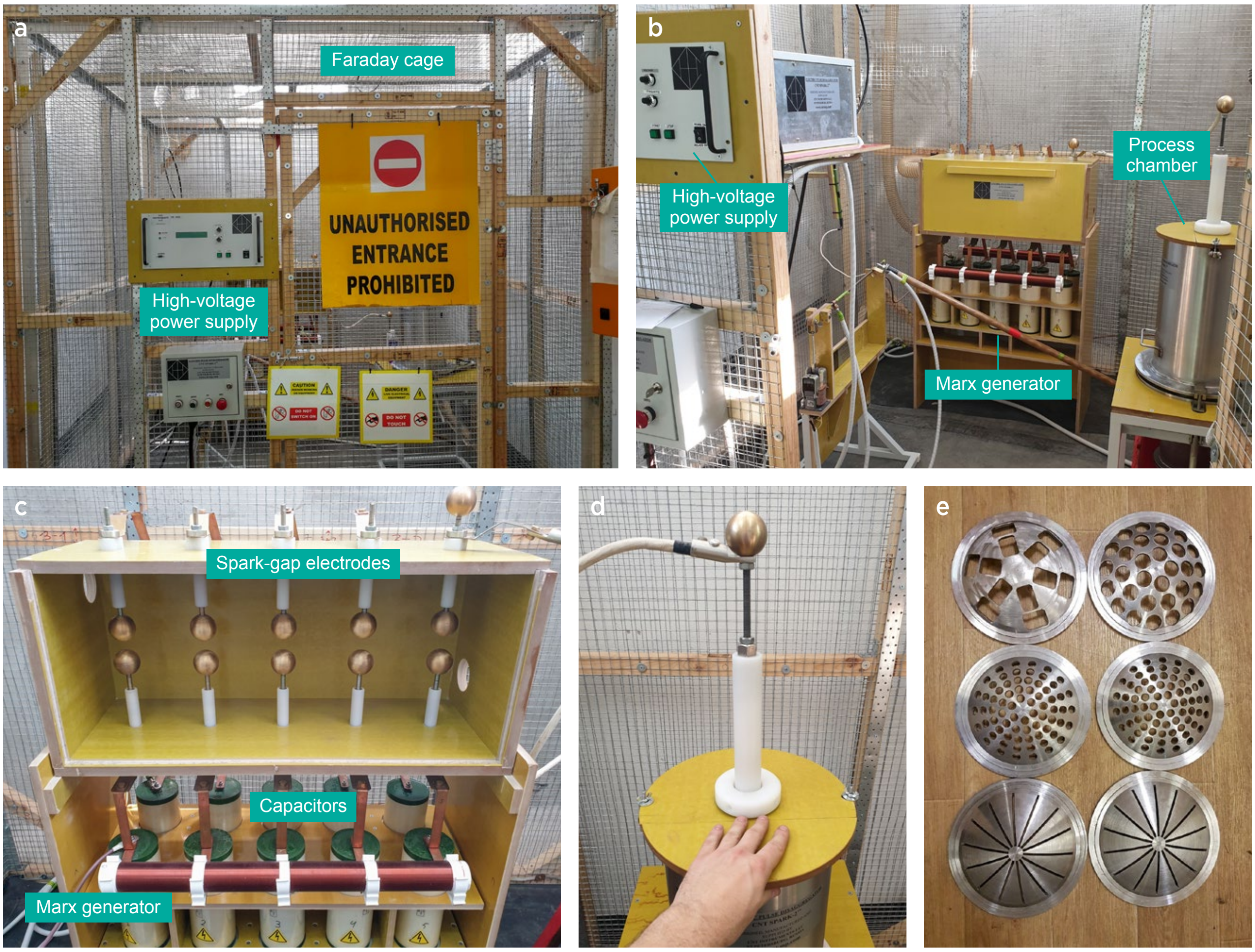

Figure 3: The EPD Spark-2 device was installed at the Kagem mine in 2019. (**a**) The equipment is housed inside a Faraday cage. (**b**) The components include a high-voltage power supply (left), Marx generator (centre) and the ore processing chamber (right). (**c**) The Marx generator consists of a series of impulse capacitors and associated spark electrodes. (**d**) Ore material is processed in a cylindrical chamber (located under a wooden lid) that is filled with water. (**e**) Sieves of various sizes can be used to suspend the ore material within the sample chamber. Photos by V. Rudashevsky and O. Alikin.

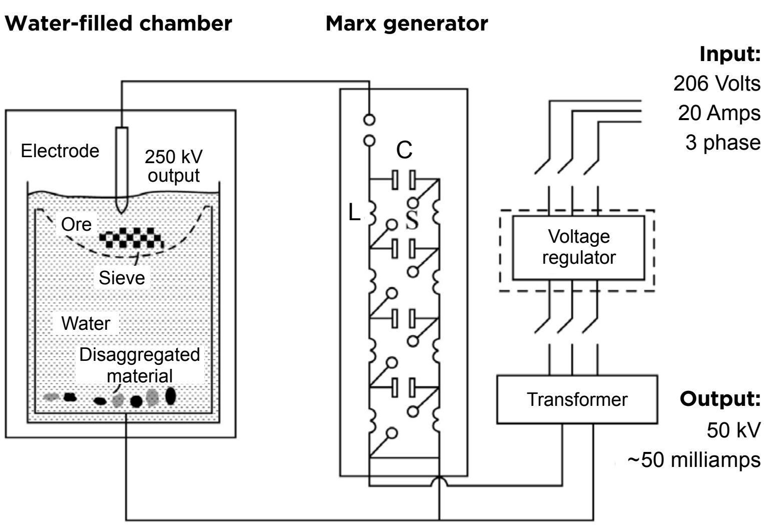

Figure 4: This simplified circuit diagram for an EPD device (adapted from Cabri *et al.* 2008) shows how the incoming current passes through a voltage regulator and then to a transformer that creates high voltage, which is then routed to a Marx generator to increase the voltage further and release it in pulses. The current is discharged into ore material that is placed on a sieve directly underneath the electrode within a water-filled container. The disaggregated material falls through the sieve and is collected in a plastic bag. Abbreviations: C = capacitor, L = inductance coil and S = spark gap.

Figure 5: For the experiments in this study, pieces of pre-tumbled emerald-bearing micaceous schist were separated into Batch 1 (left, for EPD processing) and Batch 2 (right, for hand cobbing). Photos by V. Rudashevsky and O. Alikin.

Batch 1

Electric-Pulse Disaggregtion

755 g of pre-tumbled material was processed by the EPD Spark-2 through a 16 mm sieve. The <16 mm material was separated from silt by wet-screening through a 2.8 mm sieve and then combined with >16 mm material. The total process took 2.5 minutes.

↓

Sorting and Clipping

The emeralds were much easier to clip from the gangue because of the pre-weakening of the rock by EPD. This stage took 7 minutes.

↓

Final Emerald Concentrate

The recovered emeralds were almost clean of gangue, and thus were subjected to final sorting without the need for re-tumbling. Total processing time: 9.5 minutes.

Batch 2

Hand Cobbing

Hand cobbing was performed on 750 g of tumbled material to manually liberate emeralds from gangue. This stage took 4.5 minutes.

↓

Sorting and Clipping

It was more difficult and time-consuming to clip the cobbled material compared to Batch 1. This stage took 13 minutes.

↓

Final Emerald Concentrate

The recovered emeralds had numerous gangue attachments, and thus re-tumbling would be needed for complete liberation. Total processing time: 17.5 minutes.

Figure 6: This flowchart summarises the different stages in the recovery of emeralds using EPD technology vs the conventional hand-cobbing approach.

Figure 7: Conventional hand cobbing is accomplished using a hammer in order to recover emeralds from micaceous schist. Photo by V. Rudashevsky and O. Alikin.

The processing was done using a batch mode with a plastic bag used to catch the disaggregated material. The resulting product was wet-sieved and sorted, and then prominent areas of host rock that remained attached to the emeralds were removed by manual clipping using nippers. The various fractions were then weighed.

Batch 2 was subjected to conventional hand cobbing using a hammer (Figure 7), followed similarly by sorting, clipping and weighing. The clipping was performed by the same individual who clipped the EPD-processed material to provide, as much as possible, an accurate time comparison.

RESULTS

The final weights of the emerald concentrate and gangue material (tailings) obtained by each processing technique are reported in Table I.

Batch 1: EPD Processing

After EPD processing of 755.0 g of ore material, 295 g remained on top of the 16 mm sieve, including at least four liberated emeralds that were primarily free of gangue. The smaller disaggregated fragments passed through the sieve into the plastic bag below. This material was then wet-screened using a 2.8 mm sieve to remove fine material (Figure 8), which was dried for weighing. The total time for this part of the process was 2.5 minutes. The portions captured by the 16 mm and 2.8 mm sieves were then combined for hand sorting to remove any visible emeralds

Table I: Results of processing emerald ore with EPD and hand-cobbing techniques.

Batch no.	Processing method	Initial ore quantity	Emerald concentrate	Tailings (>2.8 mm)	Tailings (<2.8 mm)	Material loss	Processing time
1	EPD	755.0 g	120.7 g	532.3 g	102.0 g	0 g	9.5 min
2	Hand cobbing	750.0 g	134.1 g	614.9 g	na*	1.0 g	17.5 min

* Abbreviation: na = not applicable, since the tailings from hand cobbing did not undergo any screening.

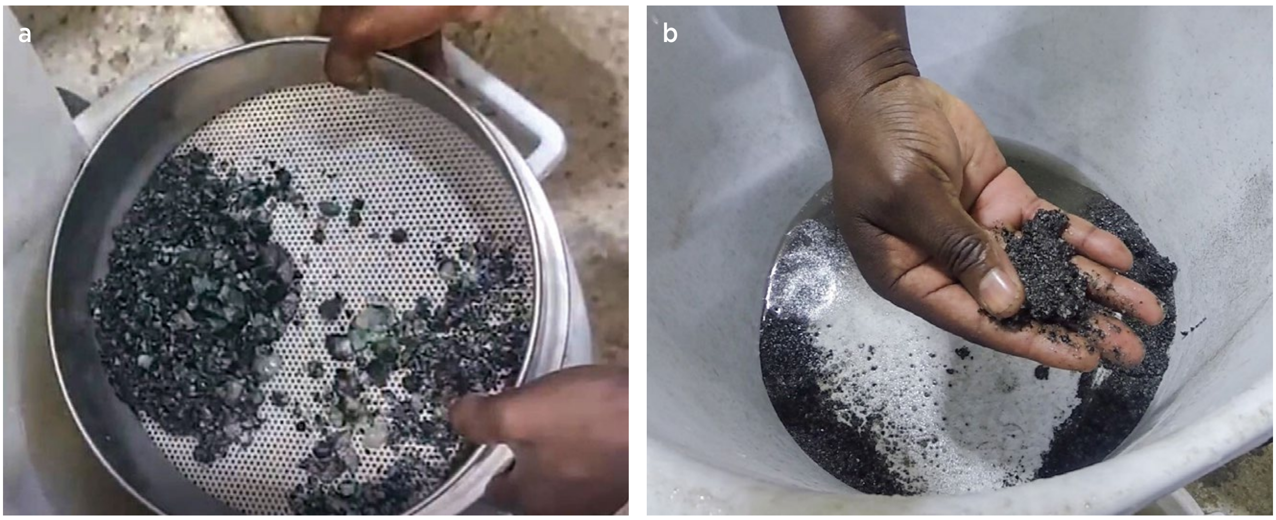

Figure 8: Disaggregated material that passed through the 16 mm sieve during EPD processing is then wet-screened using a 2.8 mm sieve (**a**) to remove waste silt (**b**). Photos by V. Rudashevsky and O. Alikin.

Figure 9: Emeralds are hand-picked from the disaggregated material after EPD processing, including some relatively large crystals. Photo by V. Rudashevsky and O. Alikin.

(Figure 9). Finally, clipping of the remaining host rock from the emerald pieces took 7 minutes. This part of the process was relatively quick and easy due to the pre-weakening of the matrix caused by EPD processing.

Overall, the emeralds were relatively clean and would not require re-tumbling prior to further sorting (Figure 10a). Thus, the total time for the complete processing of Batch 1 was 9.5 minutes.

Batch 2: Hand Cobbing

During hand cobbing, several flakes were observed to fly out of the workspace, but most of them were recovered. The weight of any lost material was calculated from the final weight obtained for this batch (Table I). Hand cobbing took 4.5 minutes and clipping took 13 minutes. Clipping of attached matrix material was more time consuming than after EPD processing because of the difficulty separating the emeralds from the host rock. Even after clipping, the manually liberated emeralds still had significant quantities of host rock attached to them (Figure 10b). This 'final' product would therefore need to undergo re-tumbling before further sorting. The total time for the processing of Batch 2 was 17.5 minutes (not including the need for further tumbling).

DISCUSSION

Based on this study, we make the following observations:

1. The weights of emerald concentrate liberated by each processing technique were similar, but the EPD-processed batch contained fewer broken crystals of emerald along with a lower retention of the micaceous matrix compared to the conventionally processed batch (Figure 10).

2. Although the amount of emerald concentrate recovered by hand cobbing was greater than for EPD processing (120.7 g/755.0 g = 16.0% vs 134.1/750.0 g = 17.9%), the emeralds obtained by EPD were more completely liberated from the matrix and had less gangue attached compared to the hand-cobbed material.

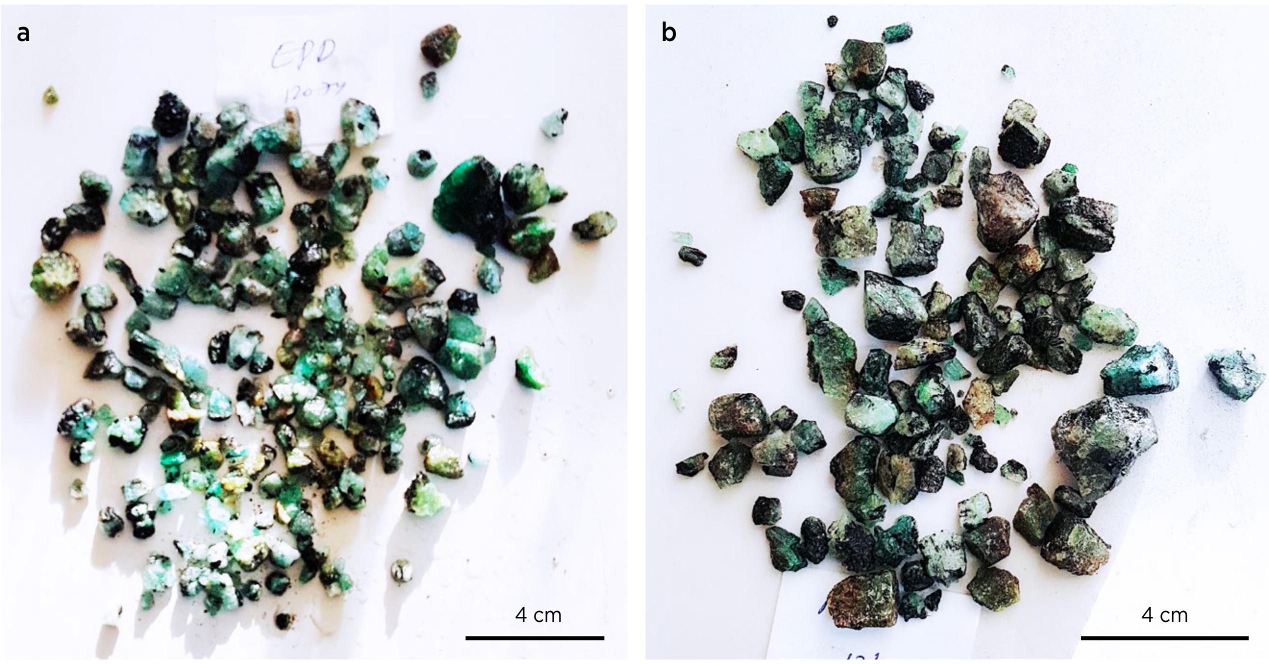

Figure 10: These photos show the final emerald concentrates recovered (**a**) after EPD processing and (**b**) after conventional hand cobbing. The EPD-liberated emeralds have very little residual micaceous schist material compared to those obtained by hand cobbing. Photos by V. Rudashevsky and O. Alikin.

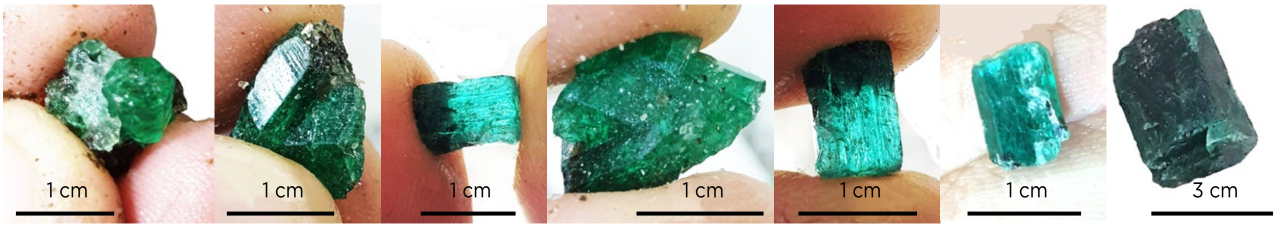

Figure 11: Close-up images are shown of some emeralds recovered by the EPD process. Photos by V. Rudashevsky and O. Alikin.

3. As expected from the commonly fractured nature of schist-hosted emeralds (due to geological forces and mining), the concentrate obtained by EPD processing was composed of emerald fragments as well as well-preserved unfractured crystals (Figures 10 and 11).

4. Since hand-cobbed material had much fewer completely liberated crystals and most of the emeralds had multiple gangue attachments (Figure 10b), it needed to be re-tumbled, which is time consuming and often rounds the crystals (thus reducing weight).

5. Overall, EPD processing took 8 minutes less than hand cobbing. Not only was the EPD processing quicker, but a further benefit was the pre-weakening of the micaceous gangue material, which made the clipping process easier and also eliminated the need for any further tumbling, saving additional time.

Another factor to consider is that the conventional hand method depends on the skill and experience of the person doing the cobbing, whereas EPD is non-operator-dependent technology. Moreover, an additional benefit of EPD processing is the prevention of theft that could more easily occur during the conventional hand-cobbing method. Currently, this technology is used to recover all of the emeralds produced from the Kagem mine (e.g. Figure 12).

CONCLUSION

The comparative experiments described in this article revealed that recovery of the emeralds from micaceous host rock by EPD technology had several advantages over the conventional hand-cobbing method. Specifically, EPD processing was faster, and any remaining gangue material could be clipped more easily due to

Figure 12: These faceted emeralds (approximately 5–8 ct) from the Kagem mine were cut from rough material recovered by EPD processing. Photo © Gemfields Ltd, 2021.

the pre-weakening effect, thus removing the need for re-tumbling of the emerald concentrate. In addition, the EPD-processed emeralds were less fragmented, and in some cases complete crystals were preserved. Moreover, since the processed material was captured inside plastic bags, there was no loss of any pieces, thus ensuring accurate monitoring of concentrates/tailings and helping to prevent theft.

Based on these advantages, we conclude that EPD processing holds the potential to become standard technology for the liberation and recovery of gems that are 'frozen' within their host rocks.

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