PROCESS INNOVATION INSIGHTS

Large **diamond recovery** and value preservation **pre-milling**

With the introduction of X-Ray Transmission technology in diamond mining, investigations into different applications have taken place, and one unique application has been developed at Lucara Diamond's Karowe Mine. This application has become known as the Mega Diamond Recovery. The application is aimed at the value preservation of the recovery of large exceptional diamonds liberated in primary crushing ahead of secondary crushing and pre-milling.

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The Mega Diamond Recovery XRT circuit at Lucara Diamond's Karowe diamond mine Botswana. (Source: Lucara Diamond)

1. Introduction

Since the introduction of X-Ray Transmission (XRT) technology in diamond mining, investigations into different applications have taken place alongside further development of XRT's application in the primary concentration process.

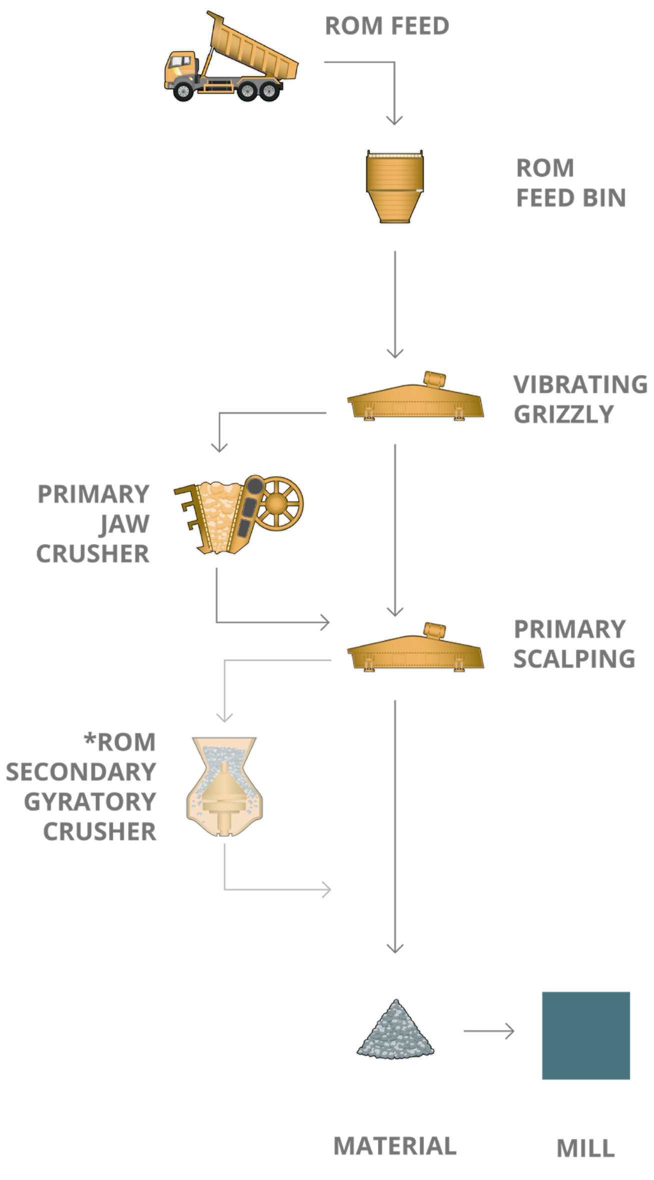


Figure 1:
*Existing pre-milling circuit at Karowe Diamond Mine. *Note: secondary gyratory crusher is not currently being used.*

Lucara Diamond's Karowe Mine, located in the Orapa Letlhakane district of Botswana (formally known as the AK06 Project), was the first operation to adopt XRT technology as its sole means of primary concentration of material in the size range -65 +8 mm.

Upon commisioning operation in April 2015, Karowe Diamond Mine started producing large diamonds in the Large Diamond Recovery (LDR) within the size fraction of -65 + 32 mm, with the likes of the Lesedi La Rona and the Constellation. Given the significance of these two finds, being the most valuable and largest gem colour diamonds, special attention was paid to all exceptional finds at this mine.

This is what led to the acquisition and commissioning of the Mega Diamond Recovery (MDR) to preserve diamond value ahead of the milling circuit.

Reports of breakage studies commissioned on selected finds indicated that several diamond fragments could be pieced together to form a larger diamond (Armstrong, 2017; Lucara, 2020).

Further investigation to assess the likely cause of the breakages pointed to a high probability of breakage arising from the secondary crushing and milling processes. This is what led to the acquisition and commissioning of the Mega Diamond

Recovery (MDR) to preserve diamond value ahead of the milling circuit.
The existing comminution design allowed for a scalping screen prior to secondary crushing, which fed the mill feed stockpile as seen in Figure 1.

The investigations led to the development of two prototype MDR options. Both options involved feeding -120 + 50 mm material prior to secondary crushing into the MDR, with the MDR tailings having the further option of either being returned to secondary crushing or sent to the mill feed stockpile (Outhwaite, 2021). The difference between the two MDR alternatives is the physical location of the MDR relative to the supporting infrastructure. The chosen MDR option is illustrated in Figure 2 (DRA. (2016). Karowe Phase 3 - MDR Circuit, Area 0010, Block Plan. Gaborone: DRA for Boteti Mining (PTY) LTD.).

The cornerstone of this paper is to elaborate on the large stone recoveries at the Karowe Diamond Mine by investigating key aspects such as the geology, prevalence of large stones, and recovery of large exceptional stones from the pre- and post-milling circuit with the addition of XRT sorters. The impact of large diamond occurrence and diamond breakage on the coarse end of the SFD models, as recovered and predicted, is also elaborated upon.

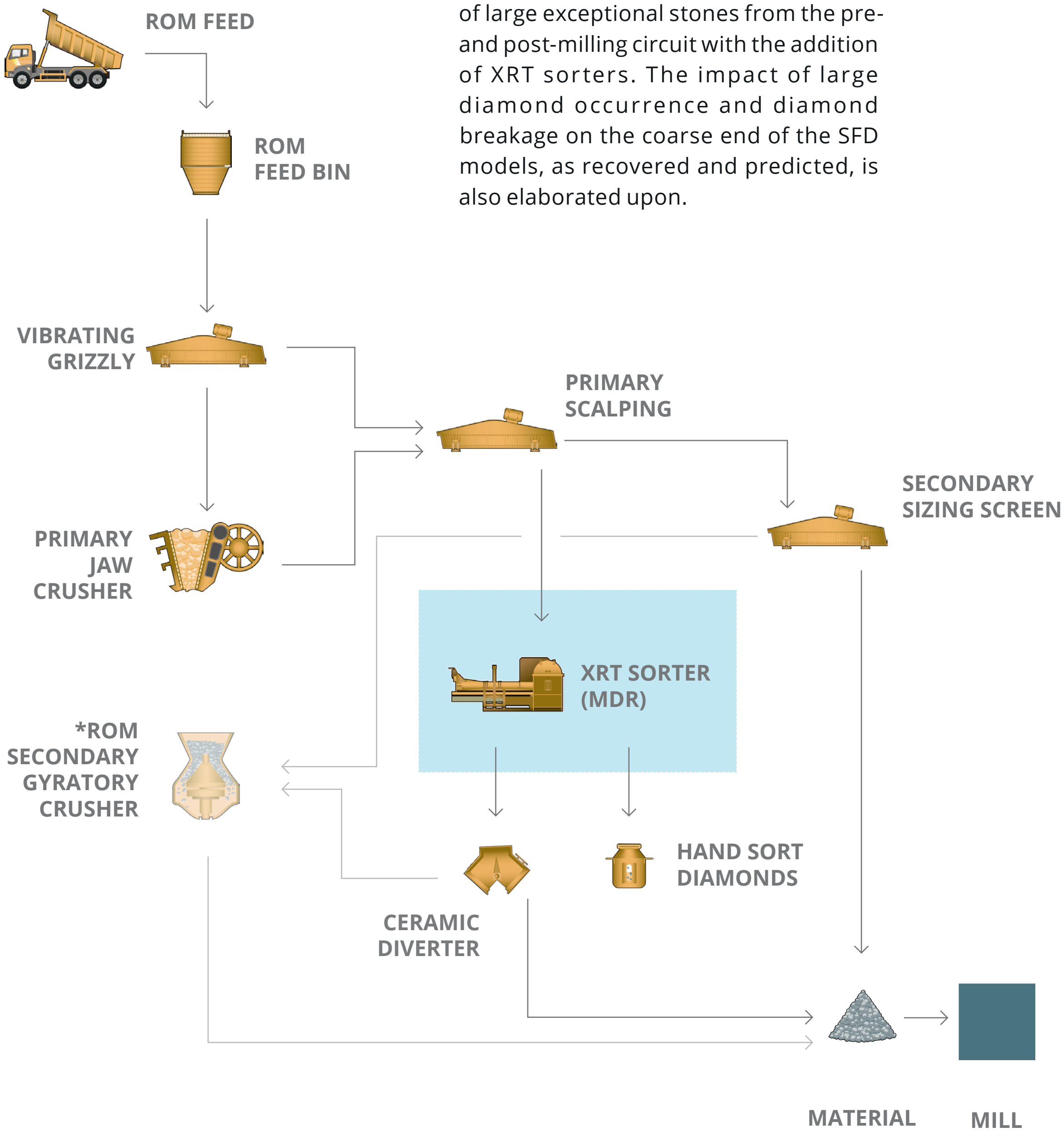


Figure 2.

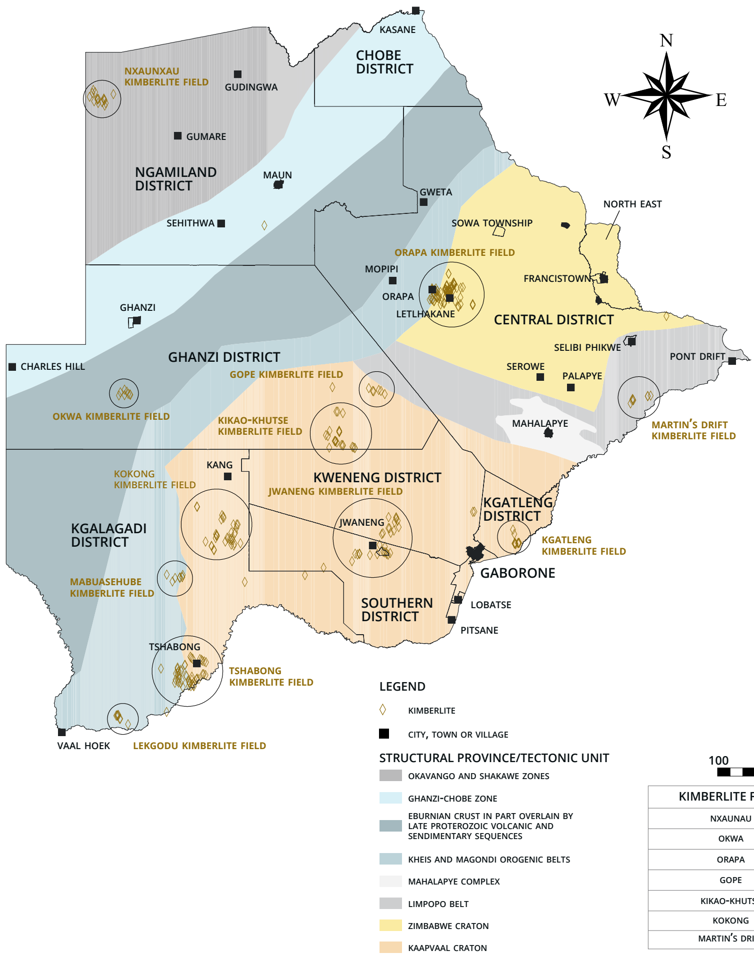
Pre-milling MDR circuit at Karowe Diamond Mine.
**Note: ROM secondary gyratory crusher is not currently being used.*

2. Geology of the AK06 kimberlite

There are twelve known kimberlite fields in Botswana. The Orapa Kimberlite Field (OKF) is located in the Central District (Figure 3). Amongst the approximately 83 kimberlite bodies within the OKF, the open-pit Karowe mine is based on the AK06 kimberlite owned by Lucara Diamond Corporation. The mine is of global significance because of its prevalence of exceptionally large, gem quality diamonds, including Type IIa.

AK06 is a roughly north-south trending elongate kimberlite body, with a surface expression of approximately 3.3 ha and maximum area of about 8 ha at approximately 120 m below surface. It comprises three geologically distinct, coalescing pipes known as the North, Centre and South Lobes. These pipes taper with depth into discrete roots as shown in Figure 4. The kimberlite in each lobe is different, in terms of its textural characteristics, relative proportion of internal country rock dilution, degree of weathering and alteration, as well as the characteristics of mantle-derived components including the diamond populations.

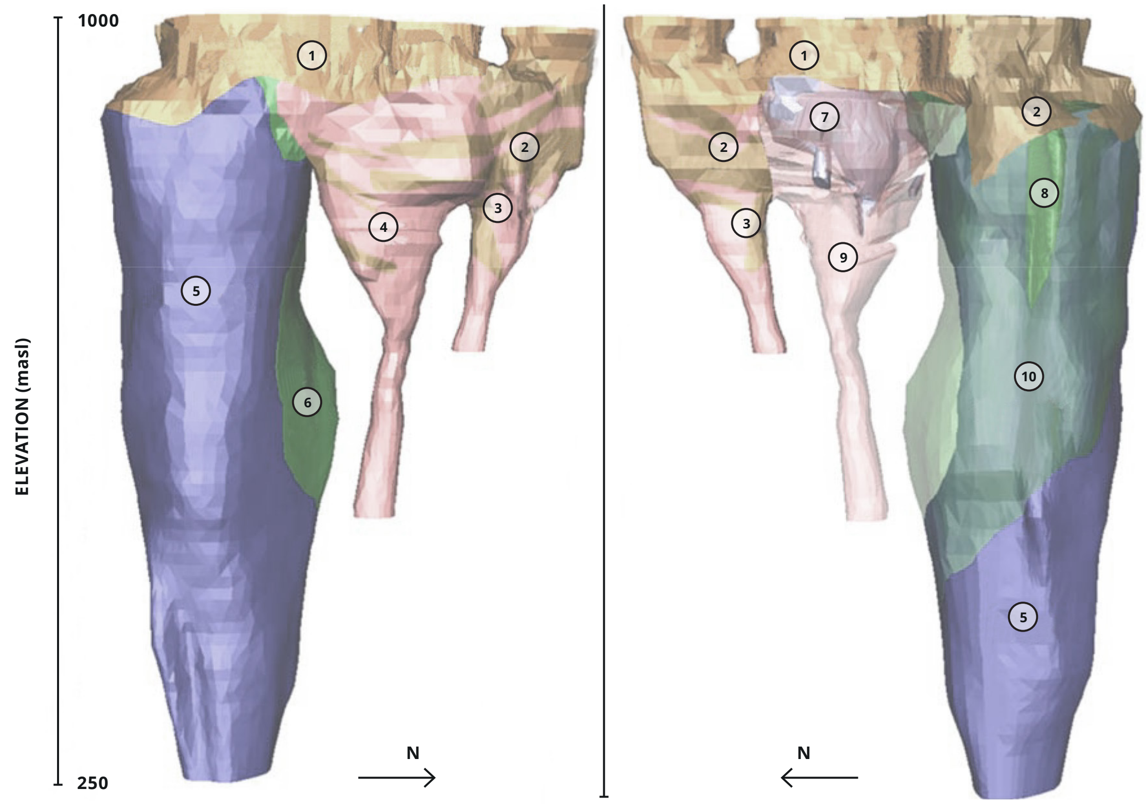
The South Lobe is the largest of the three lobes and is distinctly different from the North and Centre Lobes, which are similar in terms of their geological characteristics. The South Lobe is broadly massive and more homogeneous than the North and Centre Lobes, which exhibit greater textural complexity and more variable and higher proportions of internal country rock dilution (Armstrong, 2017).



KIMBERLITE FIELD	NUMBER	KIMBERLITE FIELD	NUMBER
NXAUNAU	27	JWANENG	28
OKWA	8	MABUASEHUBE	9
ORAPA	81	TSHABONG	86
GOPE	9	LEKGODU	8
KIKAO-KHUTSE	23	KGATLENG	11
KOKONG	76	OTHER	9
MARTIN'S DRIFT	8	TOTAL	383

Figure 3.

Overview of the 12 Kimberlite fields in Botswana. Note Orapa Kimberlite Field in the Zimbabwe Craton (yellow). (Map from Brook, 2016.)



1 UPPER WEATHERED / CALCRETIZED KIMBERLITE AND BRECCIA DOMAINS
2 BBX **3** FK (N) **4** FK (C) **5** EM/PK (S) **6** M/PK (S) **7** CFK (C) **8** WM/PK (S)
9 FK (C) – TRANSPARENT **10** M/PK (S) – TRANSPARENT

Figure 4.

Model showing the internal geological bodies in the three lobes of the AK06 kimberlite and their morphology in relation to one another (Image from Doerksen et al., 2019).

The OKF lies on the northern edge of the Central Kalahari Karoo Basin, along which the Karoo succession dips very gently to the south-southwest and off-laps against Precambrian rocks that occur at shallow depth within the Makgadikgadi Depression. The country rock at Karowe is sub-outcropping flood basalt of the Stormberg Lava Group (130 m thick), underlain by a condensed sequence of Upper Carboniferous to Triassic sedimentary rocks of the Karoo Supergroup (345 m thick), below which is the granitic basement (Doerksen et al., 2019).

The kimberlite in each lobe has been grouped into mappable units based on geological characteristics and interpreted grade potential. Units occurring in more than one lobe were modelled as separate domains for each lobe. The calcretised and weathered horizons in the upper portions of the lobes have now been mined out.

Zones of high-country rock dilution (termed breccias) are present in all three lobes, and in the South Lobe these appear to be largely restricted to the upper now-depleted portion (Doerksen et al., 2019).

The internal geology of the South Lobe is comprised of two dominant domains, identified as the M/PK(S) and EM/PK(S) domains. Additionally, this lobe contains six volumetrically minor units, one of which (KIMB3) becomes more prevalent with increasing depth in the pipe, particularly below 400 masl (metres above sea level).

A single diamond size frequency distribution (SFD) and diamond value model was used prior to 2019 to evaluate the South Lobe, as open pit production was strongly dominated by M/PK(S) material. Incremental open pit production of EM/PK(S) material was initiated in early 2018 and sufficient data has since been amassed so that distinct SFD and diamond value distribution models are now defined for both the M/PK(S) and EM/PK(S) domains in the 2019 Mineral Resource update (Doerksen, et al., 2019).

The updated 2022 Mineral Resource and Mineral Reserve statements were issued for the AK06 kimberlite in late 2021 (Lucara, 2022). The updated mineral resource is listed in Table 1.

The 2022 statement takes into account mining depletions against the Mineral Resource and Reserve statements as presented in the 2019 Feasibility Study (Doerksen et al., 2019), which build on the 2018 Resource statement from the NI 43-101 that was released in 2018 (Nowicki et al., 2018). The 2018/2019 Resource (indicated and inferred) incorporates historical drilling and sampling data obtained prior to 2018 which targeted the delineation of the deep extension of the South Lobe (deeper than 600 m from surface), as well as the geological model for the South Lobe and updates to the external contacts for the South, Centre and North Lobes. The 2022 Resource update is based on mining depletions, without changes to the grade, SFD, geological or value models.

SFD and value distribution models based on production data and discrete mine production parcels in conjunction with diamond sales data have been used to develop average price per carat (US$/ct) estimates for the North and Centre Lobes and the two dominant South Lobe rock types (MP/K(S) and EM/PK(S)). These models and estimates reflect the average diamond sales data from 2019. The value models exclude all revenue generated from diamonds sold for more than US$10M each since 2014, which include the Constellation diamond (813 ct, sold for US$63M) and the Lesedi La Rona diamond (1,109 ct, sold for US$53M).

The 2022 Mineral Resource for Karowe, as summarized in Table 1, has been classified as either Indicated or Inferred Mineral Resources, according to CIM Definition Standards for Mineral Resources and Mineral Reserves (CIM, 2014). Mineral Resources reported are inclusive of those portions of the Mineral Resource that have been converted to Mineral Reserves. The base of the Indicated Resource is at 250 masl, the base of the Inferred Mineral resource is at 66 masl and the surface at Karowe is approximately 1,010 masl (Lucara, 2022, March 30).

The MDR XRT Circuit in operation. (Source: Photo taken during site visit 2020)

2. Prevalence of large diamonds

In March 2013 Karowe produced a 239 carat Type IIa light brown diamond. This was the first indication, from production data, that the deposit hosted large +200 carat gem quality diamonds.

As mining progressed and more South Lobe material was processed, the incidence of large diamond recovery increased. In 2013 the resource model was revised to reflect the coarser SFD within the Centre and South Lobes (Lynn, et al., 2014). The 2013 Resource update for the South Lobe accounted for 3.73 weight percent (wt.%) of the production to fall in the greater than +10.8 ct size category.

Table 1.

Updated 2022 Mineral Resource Classification Domain.(Modified from Lucara, 2022)

CLASSIFICATION	DOMAIN	VOLUME (Mm^3)	TONNES (Mt)	DENSITY (t/m^3)	CARATS (Mcts)	GRADE (cpht)	AVERAGE (US$/ct)
INDICATED	South – M/PK(S)	7.83	23.18	2.96	2.495	10.8	$631
	South – EM/PK(S)	7.02	20.37	2.90	4.310	21.2	$777
	Centre	0.82	2.12	2.57	0.321	15.1	$349
	North	0.31	0.76	2.45	0.081	10.6	$222
TOTAL INDICATED		**15.98**	**46.43**	**2.91**	**7.207**	**15.5**	
INFERRED	South – M/PK(S)	0.10	0.31	3.05	0.033	10.5	$631
	South – EM/PK(S)	1.40	4.19	2.97	0.877	20.9	$777
	South – KIMB3	0.32	0.94	2.94	0.103	10.9	$631
	Centre	0.39	0.99	2.57	0.127	12.9	$349
	North	0.19	0.47	2.45	0.053	11.2	$222
TOTAL INFERRED		**2.40**	**6.90**	**2.88**	**1.193**	**17.3**	

Notes:
1. Mineral Resources are not Mineral Reserves and do not have demonstrated economic viability. All numbers have been rounded to reflect accuracy of the estimate.
2. Mineral Resources are in-situ Mineral Resources and are inclusive of in-situ Mineral Reserves.
3. Mineral Resources are exclusive of all mine stockpile material.
4. Mineral Resources are quoted above a +1.25 mm bottom cut-off and have been factored to account for diamond losses within the smaller sieve classes expected within the current configuration of the Karowe process plant.
5. Inferred Mineral Resources are estimated on the basis of limited geological evidence and sampling, sufficient to imply but not verify geological grade and continuity. They have a lower level of confidence than that applied to an Indicated Mineral Resource and cannot be directly converted into a Mineral Reserve.
6. Average diamond value estimates are based on 2019 diamond sales data provided by Lucara Diamond Corp.
7. Mineral Resources have been estimated with no allowance for mining dilution and mining recovery.

Source: Mineral resource report was prepared by Cliff Revering, P. Eng. of SRK Consulting NTD - Lucara 2021 Annual Information Form for more details (www.lucaradiamond.com.)

Production and recovery data supported a coarser SFD for the South Lobe, and subsequent adjustments to the SFD for the South Lobe have increased the modelled proportion of +10.8 ct to the current SFD for the EM/PK(S) of 8.0 wt.%, M/PK(S) of 5.9 wt.%, Centre Lobe 3.1 wt.% and North Lobe 1.0 wt.%. Models are based on actual production data from discrete production runs throughout the plant and are reflective of the current processing circuit (Doerksen et al., 2019). From Figure 5, it is clear that production in terms of +10.8 carats represents a small proportion of the overall total carats recovered, yet the value approximates to almost 70%, thus demonstrating the importance of recovering large stones.

> ***(T)he purpose of the post-primary crushing, pre-milling circuit known as the MDR circuit is firstly to preserve...***

Since commercial production was declared in July 2012 until the end of 2019, the mine has produced 213 diamonds in excess of +100 ct, including 18 diamonds in excess of +200 carats. The XRT circuit (pre-2020) was responsible for recovering thirteen +300 ct diamonds which generated revenue in excess of US$158M. In 2020 and 2021 combined, the mine recovered and produced 73 diamonds greater than +100 carats, including 18 diamonds greater than +200 carats amongst which were a 470 ct diamond, the 549 ct Sethunya, a 998 ct diamond, and a 1,174 ct diamond (Lucara, 2022). In total, at the end of 2021, the mine had recovered over 7.8 wt.% of total carats in excess of 10.8 ct for the year, which represents the highest annual volume of specials since production commenced in 2012 at Karowe.

As discussed above, the purpose of the post-primary crushing, pre-milling circuit known as the MDR circuit is firstly to preserve, and limit breakages of, large stones (-120 +50 mm) by moving the mechanical milling further downstream in the process circuit, and secondly to recover extraordinary large stones such as the 549 ct Sethunya stone recovered in 2020 from the MDR.

1,109 ct – November 2015

813 ct – November 2015

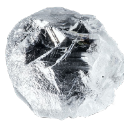
549 ct – February 2020

336 ct – August 2015

327 ct – April 2017

269 ct – May 2015

224 ct – November 2015



119 ct – December 2015

A selection of large diamonds recovered at Karowe Diamond Mine. (Source: lucaradiamond.com)

In November 2015, Karowe produced the historic 1,109 ct Lesedi La Rona diamond, the first +1,000 carat diamond recovered in over 100 years. In April 2019, the mine produced the 1,758 ct Sewelô diamond. More recently, the mine recovered a 1,174 ct diamond in June 2021 from the MDR circuit. Karowe is the only locality in recorded history to have produced three +1,000 carat diamonds. Furthermore, since 2015, 23 diamonds in excess of +300 carats have been recovered through the application of mechanical sorting, using XRT sorting technology.

At present, the Sewelô diamond is the largest mechanically sorted diamond in the world. Karowe consistently recovers +10.8 ct in accordance with the blend of ore processed (i.e. South-Centre-North). Figure 5 illustrates the cumulative carats greater than +10.8 ct on a monthly basis since 2013.

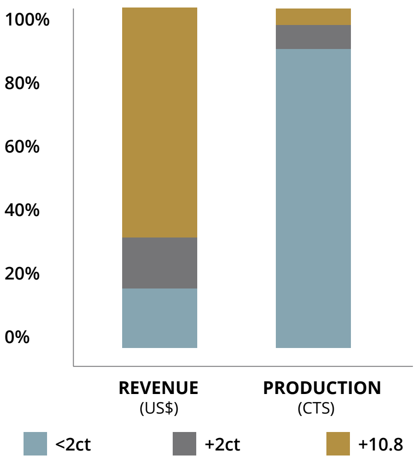
Recognition that EM/PK(S) becomes the dominant rock type with depth within the South Lobe required that a separate SFD model be generated for this unit (see Doerksen, et al., 2019). In-pit mapping and use of the updated geological model (Nowicki et al., 2018) in conjunction with production and recovery records indicate that the EM/PK(S) has produced a significant number of the large high value diamonds recovered at Karowe. These include the 1,758 ct Sewelô, an unnamed 1,174 ct diamond, the 1,109 ct Lesedi La Rona, an unnamed 998 ct diamond, the 813 ct Constellation, and the 549 ct Sethunya. Both the M/PK(S) and EM/PK(S) have a demonstrable track record for recovery of large high value diamonds.

CONSISTENT RECOVERY OF LARGE DIAMONDS

SPECIALS CONTRIBUTE ~70% BY REVENUE AND ~5% BY VOLUME HISTORICALLY

REVENUE AND PRODUCTION

INCLUDES 2015 TO 2021



2021 Recoveries:
39 diamonds >100 cts

Including:
01 diamond >1,000 cts
07 diamond >300 cts
08 diamond >200 cts
23 diamond >100 cts

Since 2012: 25 diamonds in excess of 300 carats have been recovered, including 3 diamonds >1,000 cts

11 diamonds sold for >US$ 10 million each (not included in resource value models)

KAROWE CUMULATIVE SPECIALS (ct)

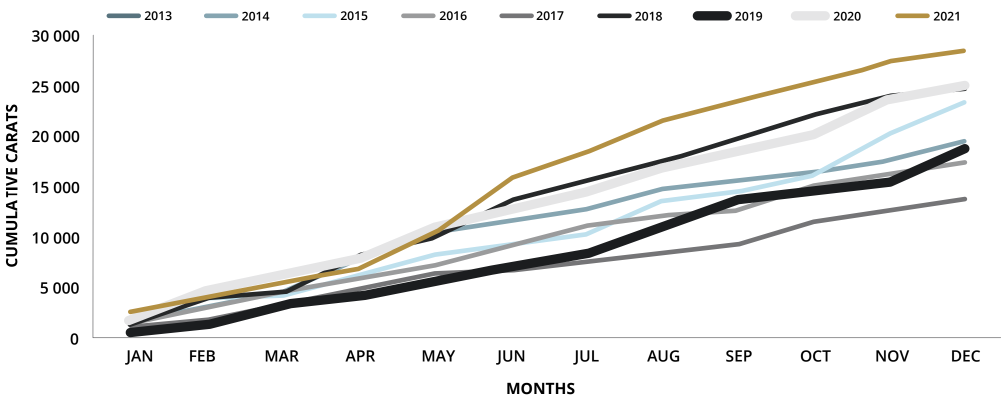


Figure 5.

Consistent recoveries of large exceptional stones. The graph on the right indicates the cumulative +10.8ct production on a monthly basis normalized to total annual production. From the trends, the constant stability in large stone recovery is evident, with emphasis on the proliferation from November 2015 (Armstrong, 2017), (Lucara, 2019) and (Lucara, 2022).

3. Size frequency distribution (SFD) of diamonds, and closing remarks

The Karowe Diamond Mine has a demonstrably coarse SFD for the Centre and South Lobes, as illustrated in the text above. Details on production SFDs for other diamond mines are difficult to access in the public domain. In general, the contribution from +10.8 ct diamonds is generally considered to be approximately 1 to 1.5 wt.%, with exceptions such as the Letšeng Mine in Lesotho.

Robust SFD models, for the various Lobes and associated domains at Karowe Diamond Mine, are developed by using discrete production parcels as per Table 2. The parcel weights are in excess of a month's production, and in the case of M/PK(S) over a year's worth of production data (Doerksen et al., 2019). As discussed above, a single SFD and diamond value model was used prior to 2019 to evaluate the South Lobe. However, over the course of 2018 and 2019, mine production from the EM/PK(S) domain was possible, allowing for the development of a distinct SFD model. Both in the M/PK(S) and EM/PK(S) domains, the SFD models slightly underestimated the percentage of the +10.8 ct size class compared to the actual production parcels. A comparison between the 2018 South Lobe SFD model and 2019 SFD models for the M/PK(S) and EM/PK(S) domains was reviewed by SRK (2019) as part of the underground feasibility study (Doerksen et Al 2019) and the major findings were evident in the +10.8ct size fraction.

Table 2.

Discrete Production Parcel Data for the Various Lobes, with a Breakdown of the Various Size Classes. (Modified from SRK, 2019, In Doerksen et Al., 2019).

SIZE CLASS	DISCRETE PRODUCTION PARCELS (ct per size class)				DISCRETE PRODUCTION PARCEL SFDS (% cts per size class)				2019 MODEL SFDS (% cts per size class)			
	M/PK(S)	EM/PK(S)	Centre	North	M/PK(S)	EM/PK(S)	Centre	North	M/PK(S)	EM/PK(S)	Centre	North
+10.8 ct	25,802	3,933	8,836	579	6.3	8.3	3.4	1.0	5.9	8.0	3.1	1.0
6-10 ct	11,852	1,417	5,626	1,140	2.9	3.0	2.2	2.0	3.5	3.6	2.9	2.4
3-5 ct	23,854	2,739	14,378	3,552	5.8	5.8	5.6	6.2	5.8	5.6	3.9	5.3
8-10 gr	22,166	2,156	14,263	4,058	5.4	4.6	5.5	7.1	4.5	4.1	7.2	7.7
3-6 gr	71,559	6,410	50,292	14,732	17.5	13.6	19.6	25.7	18.2	14.0	19.4	25.7
+11DTC	75,466	7,695	53,852	14,130	18.4	16.3	20.9	24.7	18.4	16.3	21.0	24.7
+9DTC	62,232	6,763	41,516	9,116	15.2	14.4	16.1	15.9	15.2	14.4	15.9	15.9
+7DTC	46,027	5,150	28,524	5,288	11.2	10.9	11.1	9.2	11.2	10.9	11.0	9.2
+5DTC	62,701	8,892	36,214	4,584	15.3	18.9	14.1	8.0	15.3	18.9	14.0	8.0
+3DTC	7,985	1,949	3,686	73	1.9	4.1	1.4	0.1	2.0	4.1	1.3	0.1
TOTAL CARATS	409,644	47,103	257,187	57,252								

Notes:
1. Size class abbreviations are "DTC" = Diamond Trading Company, "gr" = grainer, and "ct" = carats and resultant SFD models at +1.25 mm bottom cut-off.

As hinted to in the opening section of this paper, the breakage study conducted by Karowe played a pivotal part in the value preservation of large stones, which has a direct impact on the SFD model. SFD models are generated in the +10.8ct space alone, using individual stone weights in log-log probability space. When possible, broken diamonds are reconstructed, and the 'unbroken' distribution is compared to the 'as recovered' distribution. The +10.8 ct distribution is then modelled into the -10.8 ct space and compared to the -10.8 ct distribution (actual and model). The exercise is repeated with the -10.8 ct model projected into the +10.8 ct space. The +10.8 ct models are generated with diamonds between 30 and 80 carats in weight. Models converge during the iterative process. The +10.8 ct model also accurately predicts the proportion by weight of +10.8 ct diamonds recovered (Armstrong, 2017).

Given the recovery of diamonds in excess of +300 ct, the model for the ROM was modelled and projected into +1,000 ct space using recoveries to mid-2016. In June 2019, after recovery of the intact and unbroken 1,758 ct Sewelô, an updated ROM distribution was plotted against the 2016 model. The 1,758 ct diamond falls on the predictive model, created in 2016, on diamonds in the 30 to 80 carat size range (Armstrong personal communication ,2020).

Log-log probability plots (carats) of the +10.8 ct recovered diamond population, encompassing over 90,000 carats and over 3,200 individual diamonds, display evidence for diamond damage/loss in the +100 carat diamond sizes (see Figure 6). The evolution of understanding of the value and SFD aspects are well documented in a series of NI 43-101 reports (2014, 2017, 2018, and 2019 – available on sedar.com, Lucara Diamond Corp)

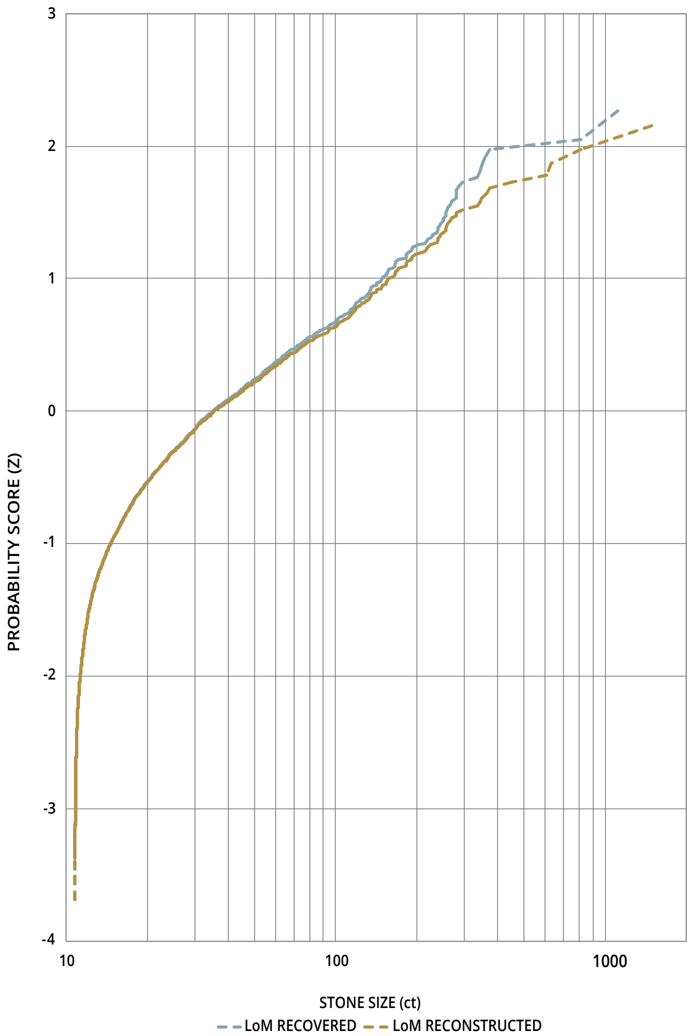


Figure 6.

Probability model (log-log plot) for AK06 LOM +10.8ct diamonds on a recovered and reconstructed basis. (Armstrong, 2017)

Reconstruction of large broken diamonds (see Figure 7 for an example) results in a coarser in-situ SFD model. There is comprehensive evidence that diamond production is impacted by the non-recovery of large +100 carat diamonds. This is due to the combination of diamond breakage (natural or mechanical) and process inefficiencies.

A more recent example of diamond breakage and value preservation could be the recovery of the 1,174 carat diamond in 2021. The MDR XRT circuit was used to recover the 1,174 carat diamond. The 1,174 diamond was likely a component of a larger diamond that weighed more than 2,000 carats. It was recovered by the MDR XRT circuit on the same production day as many other diamonds with comparable appearance (471 carat, 218 carat, and 159 carat).

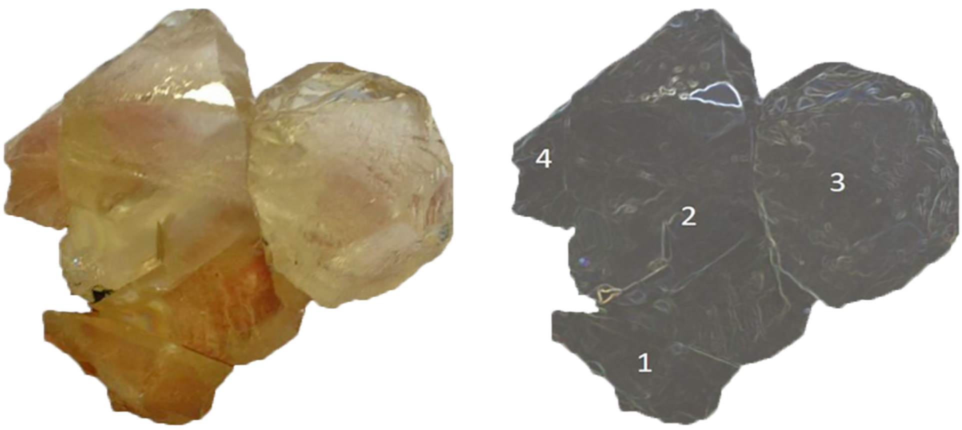
The MDR is the first possibility for diamond recovery inside the circuit; it is placed after the primary crusher and before the autogenous mill (as highlighted in Figure 2 above).

Assessment of the probability model suggests that the AK06 kimberlite will continue to produce large and exceptional diamonds, exemplified by the recovery of the 549 ct, 998 ct and 1,174 ct diamonds during 2020 and 2021.

The MDR XRT circuit is an instrumental part for ensuring that such exceptional diamonds are recovered with minimal damage. Nonetheless, the likely recovery of fragments in the MDR in 2021 indicates the need for addressing further potential breakage sources upstream of the MDR XRT sorters.

Figure 7.

Diamond breakage example at Karowe Diamond Mine. A 176.82 ct diamond broken into four distinct pieces of various sizes and shapes. (Modified from Armstrong, 2017)



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Unbroken 998 ct diamond recovered at Lucara Karowe Diamond© Mine. The 998 ct was recovered in the MDR XRT circuit. (Source: im-mining.com)