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Special Publication Number 20

**Geoscience and Exploration of the  
Argyle, Bunder, Diavik, and Murowa  
Diamond Deposits**



*Editors*

**Andy T. Davy, Chris B. Smith, Herwart Helmstaedt,  
A. Lynton Jaques, and John J. Gurney**

**SOCIETY OF ECONOMIC GEOLOGISTS, INC.  
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*On the cover:* Photograph of rough and resultant polished diamond from the Diavik deposit, Northwest Territories, Canada. *Back cover:* Top row, left to right: Aerial view of the Diavik mine site, and signature rough and polished pink diamond from the Argyle deposit (Western Australia, Australia). Middle row, left to right: Examples of white gem diamonds from the Diavik and Argyle deposits. Bottom row, left to right: Diamonds from the Diavik, Argyle, Murowa (south-central Zimbabwe), and Bunder deposits (Madhya Pradesh, India), respectively.



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## Foreword

Stephen McIntosh

*Group Executive, Growth and Innovation, Rio Tinto*

The idea for this Society of Economic Geologists (SEG) diamonds volume was conceived a little over a decade ago by the former head of exploration at Rio Tinto, Eric Finlayson. The goal was to produce a comprehensive and compelling account for our own exploration and resource geologists, potential business partners, and those in the broader diamond industry and in academia. The result presented here is a retrospective that is both a technical record and a statement of capability, which elevates the published information on diamond exploration and evaluation to a new level.

Rio Tinto has a proud history in diamond exploration that spans more than four decades. Our entry into the diamond industry dates back to 1977 with the discovery of the Ellendale lamproites in Western Australia. The discoveries detailed in this volume (Argyle, Bunder, Diavik, and Murowa) were made by Rio Tinto and its partners.

It is not just discovery success we wanted to capture in this volume. We have sought to balance the history of diamond exploration and discovery with perspectives from academia on mantle minerals and diamonds as well as innovation in orebody evaluation techniques.

The breadth and longevity of the Rio Tinto exploration programs and the technological advancements across our portfolio have enabled us to innovate and apply these advances in our diamond exploration activities. We've invested in indicator mineral chemistry, looking beyond the traditional indicator mineral suite with chromite, a critical differentiator in the

discovery of Argyle. We've also pioneered the use of microdiamond stone counts to make macrodiamond grade estimation more robust and cost-effective. Both are critical tools used across our portfolio and prospects today.

A publication of this quality and scope is a very significant undertaking, and I'd like to thank the SEG for providing the platform to publish this diamonds retrospective. The support and efforts of Stuart Simmons and Brian Hoal at the SEG are specifically acknowledged. Since we began the volume in 2012, there have been a number of people whose dedication and hard work have been instrumental in bringing the project to fruition. I'd like to recognize two pivotal contributors in Chris Smith, former chief geologist for Rio Tinto Diamonds, and Andy Davy, consulting geologist–diamonds. Chris championed innovation in diamonds exploration, the establishment of our laboratories, and use of indicator minerals, and Andy drove the development of our microdiamond evaluation protocol, which remains a critical tool for our diamonds exploration programs and for orebody grade estimation.

I'd also like to thank Paul Agnew, chief geologist–technical support and technical development, and Alan Kobussen, principal geologist, for their tireless work in guiding the production, review, and approvals for this publication.

This volume is the first of its kind and a unique reference we hope will be leveraged and valued by generations of explorers to come, not just for the legacy learnings but for the valuable inspiration it provides for future innovation in the industry.

## Acknowledgments

This volume was conceived by Eric Finlayson and Andy Davy and supported strongly by Stephen McIntosh (Rio Tinto Exploration) and Bruce Cox (Rio Tinto Diamonds), and we acknowledge also the organizational role played by Alan Kobussen, who helped bring the volume to completion.

The volume is dedicated to Rio Tinto's legacy in the diamond business. We hope it will inspire a new generation of exploration geologists to make discoveries of primary diamond deposits, leading to the development of a suite of twenty-first century operating mines.

Our thanks to the key individuals who have championed diamonds within Rio Tinto, especially Chris Smith, whose keen observations, insights, enthusiasm, persistence, and inquiring scientific approach, including constantly challenging conventional wisdom and dogma, were important factors that led to the discovery of the Ellendale pipes and then Argyle. It is impossible to mention everyone who has helped to build Rio Tinto's diamond business, but the common theme among

those people has been their dedication and commitment to working with this most fascinating commodity. Diamonds are intriguing, beautiful, and challenging to locate. Let us hope there are always more to find.

This Special Publication was assembled with the help and patience of the Society of Economic Geologists. Rio Tinto is particularly grateful to Brian Hoal, Stuart Simmons, Rich Goldfarb, Larry Meinert, Christine Brandt, and Vivian Smallwood for their hard work—especially Stuart, who was the SEG's lead technical editor.

Finally, we thank the authors for their efforts and patience, and the reviewers who generously gave their time. The reviewers for this volume are listed below, with the exception of those who elected to remain anonymous.

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## Geoscience and Exploration of the Argyle, Bunder, Diavik, and Murowa Diamond Deposits: Preface

This volume provides descriptions of the geology, diamonds, mantle settings, exploration techniques, and evaluation methods of four major primary diamond deposits discovered by Rio Tinto and its partners<sup>1</sup>: Argyle in Australia, Bunder in India, Diavik in Canada, and Murowa in Zimbabwe. Argyle has been the world's largest individual diamond producer by carat weight, with production since December 1985 totaling 848 million carats (Mct; Fig. 1; Rio Tinto, 1985–2017). The Atri pipe at Bunder has been evaluated to 250 m below surface for grade and near surface only for diamond pricing, but the mineralization is estimated at 32 Mct (Fig. 2; Rio Tinto, 2008). The Diavik mine commenced production in December 2002 and, to date, has produced 115 Mct of diamonds (Fig. 3; Pollock et al., 2018). Production from Murowa over

the period 2004 to 2014 has been 4 Mct (Fig. 4; Rio Tinto, 2004–2014). These outputs per individual mine may be compared with global diamond production for the year 2016 of 127 Mct (Kimberley Process, 2018) and make Rio Tinto one of the world's largest diamond producers.

What can we learn from Rio Tinto's exploration and evaluation programs, and is there a common theme? The locations of these deposits range in climate from arctic (Diavik) to tropical (Bunder), requiring different exploration techniques to be used for their discovery. Argyle, Murowa, and Bunder were discovered by greenfields exploration underpinned by solid area selection criteria. Rio Tinto recognized that extrusive ultramafic rocks could be present in mobile zones along craton margins, and drainage sampling for chromites and diamonds in these areas led to the discoveries of Argyle and Bunder. Conversely, the Murowa and Diavik deposits were found on craton by searching for traditional kimberlite indicator minerals in drainage and glacial till samples, respectively.

<sup>1</sup> Aber Resources (now Dominion Diamond Mines), Rio Tinto Zimbabwe (now RioZim), Tanganyika Holdings, and Ashton Mining & Northern Mining (no longer in existence).



Fig. 1. Run-of-mine +11 Diamond Trading Company (DTC)-sieve-size diamonds from the Argyle exploration drift at 9,860 RL in the South Sandy Low ore domain, 2005. The proportion of gem diamonds is approximately 10%. Note: The average weight of a +11 DTC-sieve-size diamond is 0.45 ct. Gem diamonds are defined as sawables and makeables—all qualities and all colors.



Fig. 2. Run-of-mine +11 DTC-sieve-size diamonds from Atri South pit sample #11A in the SPL3 geologic unit, Bunder diamond deposit, 420-m elevation, 2010. Parcel weight is 77.72 ct. The proportion of gem diamonds is approximately 30%.

Excepting Diavik (the ground was staked adjacent to a newly discovered kimberlite province), greenfields programs of four to five years were required to convert very large areas of ground into discoveries. The key elements of success were unwavering support from executive management, enthusiastic, keen, and dedicated teams of geoscientists, and open and direct communication between the sampling teams in the field and the mineralogists in the laboratory back at base. Also, in-house sample processing facilities proved to be invaluable in ensuring the highest-quality treatment of samples, quick turnaround, and the ability to rapidly reset sampling priorities (Argyle, Murowa, and Bunder).

The Kimberley craton-wide exploration program that led to the Argyle olivine lamproite discovery (Smith et al., 2018a) commenced with a search for lamproites in the West Kimberley region of Australia, based on the suggestion that the known leucite lamproites were differentiates from peridotite magma, similar to kimberlite. However, the then-known leucite lamproites carried little in the way of olivine or mantle-derived minerals such as pyrope and diamond. Picrolilmenite and other megacryst minerals characteristic of group I kimberlite were also absent. Olivine weathers in a tropical environment, suggesting that any olivine lamproite pipes might not crop out. This hypothesis was proven correct with the discovery of the first olivine lamproite at Big Spring (Smith et al., 2018a) that was associated with a halo of magnesiochromite in the surrounding soil, as well as occasional diamond and

pyrope. The recognition of chromite as a key indicator mineral proved invaluable to Rio Tinto and its partners' exploration programs around the world. Chromite presence, together with diamond, characterizes the stream drainage trails that led to the discoveries of Argyle (Smith et al., 2018a), Murowa (Sims et al., 2018), and Bunder (Krishna et al., 2018). The geophysical methods (especially magnetics and electromagnetics) and soil geochemistry that were used in the follow-up of indicator mineral anomalies to pinpoint and define the shapes of the kimberlite and lamproite bodies are described. In Canada, sampling of glacial deposits and lake shore sediments for indicator minerals led to the discovery of the Lac de Gras kimberlite field. In the staking rush that followed, Kennecott (a Rio Tinto subsidiary) and partners took title centered over the lakes under which the Diavik pipes were subsequently found. Brett et al. (2018) describe the methods used to locate the Diavik pipes, including till sampling for indicator minerals and airborne geophysics.

Evaluating diamond deposits is time-consuming and expensive. After more than 130 years of "mechanized mining," very few geoscientists comprehend the challenge facing them when they embark on the evaluation of new diamond deposits. It is unlikely that a kimberlite or a lamproite comprises a single eruptive event, magma phase, or geologic unit. Our experiences on Rio Tinto's deposits taught us that each geologic unit contains a different diamond population. Therefore, unlike metalliferous deposits, such as gold and copper,

where the product always has a consistent value, diamond values (prices) can change within deposits and between deposits that are as little as 100 m apart. The inherent variability in the value of the product means that large parcels of diamonds must be recovered from each geologic unit before ore values can be estimated, adding to the complexity and the cost of the orebody evaluation. Sampling for grade resolves only half of the economic equation; spatially representative sampling is also required for determining the diamond price.

Our principal learning from drill sampling, bulk sampling, and processing special batches of each geologic unit is that the diamond color, clarity, and shape distributions can change with size. Consequently, it is inappropriate to assume that the quality distribution in the finer-size diamonds represents the quality distribution in the coarser-size diamonds (Pollock et al., 2018). The implications for orebody evaluation are that much larger diamond parcels are required to reduce uncertainty in the run-of-mine price estimate than have been reported in the literature to date. The same argument can be used for the diamond size distribution; it is inappropriate to assume that the form of the size-frequency distribution in the finer sizes can be extrapolated into the coarser sizes.

The evaluation process does not vary in its elements; vertical and angled slim-hole drill core is a basic requirement for geology, orebody delineation, and rock density determination. Large-diameter core or reverse-circulation drill chips are required for grade determination, and large-diameter, reverse-circulation drilling and underground bulk sampling

are necessary for price determination. The rock characteristics and the grade of the deposit influence selection of sample type and drill-hole diameter. The higher grades at Argyle and Diavik meant that smaller samples of rock could provide meaningful grades, causing Rio Tinto geologists to select 8- and 6-inch-diameter drill core, respectively, for the initial evaluations of these deposits, followed by underground bulk sampling for larger diamond parcels for price determination. Larger deposits require more sampling, incurring higher costs. In an effort to reduce these costs at Argyle, Rio Tinto geologists recognized that the high grade and the very fine diamond size-frequency distribution would facilitate reducing sample sizes if the diamond size-frequency distribution demonstrated spatial consistency within a geologic unit over the 0.1- to 10-mm size range. Diamond size-frequency data from 1-, 100-, and 100,000-tonne samples were gathered to prove with high levels of confidence that stone counts per unit sample weight for -1-mm (micro) diamonds recovered by processing NQ drill core using caustic fusion could be used to predict +1-mm (macro) diamond sample grades. Taking this approach reduced the costs of grade estimation at Argyle by an order of magnitude (Roffey et al., 2018).

The four deposits provide a contrast in tectonic settings, as discussed by Helmstaedt (2018), who found that the kimberlites (Diavik and Murowa) are situated within stable Archean cratonic nuclei, whereas the lamproites (Argyle and Bunder) are located at craton margins subjected to extensive Proterozoic deep faulting. Nevertheless, diamonds with harzburgitic



Fig. 3. Run-of-mine +11 DTC-sieve-size diamonds from an underground bulk sample (155-m level) of the A154 North MK geologic unit, Diavik diamond deposit, 2006. The proportion of gem diamonds is approximately 20%.



Fig. 4. Run-of-mine +11 DTC-sieve-size diamonds from a production batch on the 665 level in the K2 pipe, Murowa diamond deposit, 2015. The proportion of gem diamonds is approximately 40%.

mineral inclusions are present in all four deposits, reflecting their sourcing from the Archean cratonic nuclei. Diamonds with eclogitic inclusions of Proterozoic age are prominent at Argyle and also occur at Diavik, suggesting the addition of crustal carbon by subduction to the Archean cratonic roots.

The differing tectonic setting of the four deposits may also explain the differing nature of their diamond host rocks. Based on their mineralogy and geochemistry, the Diavik (Moss et al., 2018b) and Murowa pipes (Moss et al., 2018a) are classic group I kimberlites situated on stable Archean cratonic blocks with deep lithospheric roots (Aulbach et al., 2018; Bulanova et al., 2018a; Hunt et al., 2018; Pearson et al., 2018). In contrast, the Argyle pipe is the first major diamondiferous ore deposit found that is hosted by lamproite (Rayner et al., 2018) and situated in a Proterozoic orogenic belt at the craton margin (Jaques et al., 2018), a setting not previously considered prospective for diamond pipes. Unlike kimberlite, the Argyle ultramafic rocks contain pseudomorphs after leucite and other minerals diagnostic of lamproite, have high  $K_2O/Na_2O$ , high  $TiO_2$ , and  $K_2O$  but low  $CaO$  contents, and are inferred to be from cratonic lithospheric mantle sources that have undergone multistage, time-integrated geochemical enrichment. Likewise, the Atri pipe at Bunder has lamproite affinities in terms of its mineralogy (Das et al., 2018) but geochemically resembles group II micaceous kimberlite (orangeite), and it has Sr and Nd isotope compositions more consistent with archetypal group I kimberlites. Consequently, both Atri and the neighboring diamondiferous body at Majhgawan are

considered to be transitional between group II micaceous kimberlite and lamproite. As both Argyle and Bunder are located on the margins of Archean cratons, this volume provides the opportunity to review the contrasting tectonic settings of the two main primary diamond hosts—kimberlite and lamproite (Helmstaedt, 2018).

The mantle sample provided by these occurrences varies considerably. Mantle xenoliths and heavy mineral concentrates documented from Argyle so far are entirely peridotitic in origin, but the inclusions recorded in diamond are overwhelmingly eclogitic in origin. New data presented by Jaques et al. (2018) and Stachel et al. (2018) highlight this interesting discrepancy and explore the differing geneses of these two mantle components. At Diavik, there is a more usual mix of peridotitic and eclogitic material, which has been well studied. Aulbach et al. (2018) provide a review of the state of knowledge of the mantle root beneath the central Slave craton gained from these materials and offer some new insights into the chronology of root formation and preservation. The mantle sections beneath both Murowa and Bunder (Atri) are unusual in that they appear to be composed almost exclusively of peridotitic material with little evidence of an eclogitic component. Relatively less is known about the mantle sections beneath these areas of the lithosphere as few studies have been published. Pearson et al. (2018) provide an update on the geochemistry of the mantle beneath the southern Zimbabwe craton at Murowa, including new thermobarometric data and Re-Os isotope data. Kobussen et al. (2018) present

the first significant indicator mineral chemistry dataset for the Atri occurrence, including estimates of the geotherm and identification of distinct geochemical domains within the mantle section.

Finally, the study of diamonds and their inclusions from each of the four occurrences shows how a diversity of tectonic and geologic environments can result in diamonds with wide-ranging properties, but all ultimately result in economic deposits. Diamonds from Diavik (Hunt et al., 2018) and Murowa (Bulanova et al., 2018a) are typically colorless octahedra of good gem quality. In contrast, diamonds from Argyle (Bulanova et al., 2018b; Stachel et al., 2018) and Bunder (Smith et al., 2018b) are predominantly brown, resorbed dodecahedra with a significant proportion of stones of industrial quality. Nevertheless, Argyle is famous for its fancy, valuable pink diamonds, rare blues, and cognac-colored brown gemstones (Bulanova et al., 2018b). Diamonds from Argyle contain a predominance of eclogitic inclusion minerals thought to be indicative of derivation from ocean-floor material subducted to deep lithospheric mantle depths (Stachel et al., 2018), in keeping with the structurally complex tectonic setting. The minor diamond component with peridotitic inclusions is from shallower depths in the mantle (Bulanova et al., 2018b) and, in conjunction with the presence of peridotitic xenoliths within the lamproite, indicates the presence of cratonic peridotitic lithosphere beneath the Proterozoic Halls Creek orogen, as described by Jaques et al. (2018).

When the work on this volume commenced, Rio Tinto was active on all four deposits, but circumstances have changed. Its share in the Murowa kimberlites was sold to RioZim, and its ownership of the Bunder lamproites was handed back to the Madhya Pradesh government. The Argyle mine is now nearing the end of its economic life and, at Diavik, production is likely to cease in 2025 because the kimberlites shrink to only a few meters in diameter at depths of 700 m below surface. Rio Tinto's participation in the diamond industry may well be extended thanks to the kimberlites in the Fort à la Corne field in Saskatchewan, Canada, in which it is earning an interest, but the evaluation and mining of these extensive, low-grade deposits present challenges of a dimension so far not encountered by the industry at large.

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