LONDON'S GLOBAL UNIVERSITY

CENG0037 MSc Research Project

Economic assessment of using MinEx CRC's downhole LIBS tool in an mineral exploration scenario

by:

Yifan YANG

Student's registration number: 23049743

Supervisor(s): A/Prof. Caroline Tiddy

Dr Ben van de Hoek

A thesis submitted to the University of London for the degree of Master of Science

Department of Chemical Engineering

University College London (UCL)

September 2024

Declaration

I, Yifan Yang, confirm that the work presented in this thesis is my own.

Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Word count: 5901

(excluding the title page, table of contents, references, tables, figures and appendices)

Has the written report been submitted on Moodle?	Yes
Have relevant source codes and/or raw data been submitted on Moodle?	Yes
Has the lab space used been cleaned up (if applicable)?	N/A

...............Yifan YANG..................	........Yifan Yang........	.....2024/8/27.....
Student's Name	Student's Signature	Date

ABSTRACT

This thesis presents a comprehensive economic assessment of the downhole Laser-Induced Breakdown Spectroscopy (LIBS) tool, comparing it to portable X-ray fluorescence (pXRF) and traditional laboratory assays in the context of mineral exploration. The primary objective is to evaluate the cost-effectiveness and operational efficiency of these technologies to identify the most suitable method for modern exploration. Amidst increasing global demand for metals driven by technological advancements and population growth, efficient exploration methods are essential. While traditional laboratory assays provide precise data, they are slow and costly. Portable technologies like pXRF offer rapid on-site analysis but struggle with detecting light elements and maintaining accuracy in varied field conditions. The study's findings reveal that despite higher initial costs, the downhole LIBS tool significantly enhances long-term value through operational efficiency and real-time data acquisition. It minimizes the need for extensive sample transportation and laboratory analysis, reducing overall exploration costs and environmental impact. The LIBS tool's adaptability in challenging environments further underscores its potential as a vital asset in mineral exploration. In contrast, pXRF, while convenient and less expensive initially, is limited by its inability to accurately measure lighter elements like sodium, which are crucial in geochemical analysis. Laboratory assays, although the most accurate, are impractical for real-time decision-making due to their time-consuming nature. In conclusion, this thesis establishes downhole LIBS as a transformative technology in mineral exploration, combining efficiency, accuracy, and cost-effectiveness. Its adoption aligns with the industry's shift towards more sustainable and efficient exploration practices, promising to improve both economic outcomes and operational success.

Contents

INTRODUCTION

Fueled by the appeal for innovative and green technologies such as electric vehicles and renewable energies, as well as the expanding global population and rising living standards, there is an ever-increasing global demand for metals and thus new mineral deposits (Backman, 2008). Nevertheless, the worldwide patterns of diminishing mineral reserves for numerous commodities and escalating exploration expenses indicate that the methods of exploration are inadequate and/or are not being utilized optimally (Harmon et al., 2019). Exploration is also hindered by the lower ore grade of minerals in deeper and more challenging nature of deposits (Harmon et al., 2019). Exploration activities may be enhanced by developing methods for more efficient, rapid and cost-effective methods of quantifying the geochemistry of rocks during exploration (Janoušek et al., 2006).

Recent technical advancements in mineral exploration have seen the implementation of on-site or portable instrumentation, on-site laboratory technologies, a range of core scanners, and fluid analysis technologies. Portable or field technologies, such as portable X-ray Fluorescence (pXRF), powder X-Ray Diffraction (XRD), portable spectral technologies, and Laser-Induced Breakdown Spectroscopy (LIBS) assist in acquiring chemical and mineralogical data (Laperche & Lemière, 2020). Among all, laser-based spectroscopic techniques are becoming increasingly significant for chemical analysis due to their potential for precise, non-invasive, and very sensitive detection and analysis of solid, liquid, aerosol, and gaseous substances in real-time (Harmon et al., 2009; Fontana et al. 2021). Laser-induced breakdown spectroscopy (LIBS) is a specific technique that falls into this category. LIBS, which is presently undergoing rapid research and development as a technology for geochemical analysis, is attractive potential as a field tool for rapid man-portable and/ or stand-off chemical analysis (Harmon et al., 2009; Fontana et al. 2021; 2023a; 2023b). The adaptability of the probe design and the utilization of fiber-optics has rendered LIBS very suitable for distant measurements (Jain et al., 2017). It should also be noted that the mining exploration scenario must prioritize two crucial objectives: offering a cost-effective alternative to traditional laboratory analysis programs and maximizing cost-benefit ratios in the discovery and development of new mineral deposits (Dhillon, 1978; Lemiere, 2018).

This dissertation presents an economic assessment of a new downhole LIBS tool being developed within Mineral Exploration Cooperative Research Centre (MinEx CRC) Project 3: Real-time Downhole Assay. The LIBS tool will be compared with the more established portable XRF technique and laboratory assay. The assessment will include calculation of the cost of deployment of the downhole LIBS tool and portable XRF tool including instrument purchase, labour, training, maintenance cost and time. The economics of deploying the downhole LIBS tool versus using the portable XRF will be compared in a real-world exploration scenario considering the instrument limitations (e.g., range of elements analyzed), deployment time and cost. The implications of commercial benefits LIBS tool are then discussed in the context of the exploration scenario.

BACKGROUND

Geochemical data play a crucial role in driving informed decisions in mineral exploration, benefiting the economy, environment, and society as a whole. It can greatly influence our understanding of natural contamination of the source rock or the consequences of urban activities that lead to local pollution. Assistance is needed in finding and evaluating the economic viability of mineral deposits (Ali et al., 2017, Grunsky et al., 2017).

Geochemistry and mineral exploration

The economic well-being of our societies and the quality of our lives are closely tied to our capacity to discover, utilize, and oversee our metallic and mineral reserves. Metal and mineral deposits are considered geochemical anomalies, and geochemistry is crucial at every level of the mineral resources value chain, starting from early exploration to mine closure (Kyser et al., 2015). The primary emphasis of geochemistry in mineral exploration is to identify and map trends in the chemical composition of the lithosphere or biosphere that are indicative of mineralization (Cohen & Bowell, 2013).

Geochemists utilize the principles of element mobility, such as transport and fixation, in the near-surface environment to identify mineral deposits underground, determine the distribution of elements in and around these deposits, evaluate the overall geochemical conditions, and improve efficient and environmentally friendly methods for extraction and waste disposal. In such process, geochemistry is essential in developing the methods to effectively manage metal resources and ultimately contribute to the betterment of society (Kyser et al., 2015).

Geochemical assay techniques

Downhole LIBS geochemical assay

Laser induced breakdown spectroscopy (LIBS) is a straightforward spectrochemical technique that uses a pulsed laser to generate a plasma. The laser beam is concentrated on the sample's surface, resulting in a rapid and substantial deposition of energy on a small area. Rapid heating of the materials results in the process of ablation and vaporization of the material. The vapor undergoes absorption of a portion of the laser energy, resulting in an increase in temperature and ionization (Kanyinda Jean-Noëla et al., 2020). The laser plasma is formed in a confined space, ensuring that only a minuscule amount of sample is involved in each laser microplasma event (Harmon et al., 2009; Sandtke, 2019).

LIBS enables the precise and immediate study of the elemental chemical composition of a sample, whether it is in a solid, liquid, gaseous, or aerosol state, directly at the location where it is situated. This technology possesses the added benefit of being adaptable to various forms, allowing it to be used in any type of context, whether it be online measurements in an industrial setting, direct analyses in the field, or laboratory analyses (Kanyinda Jean-Noëla et al., 2020).

Currently, LIBS technology is utilized to fulfill the requirements of detection and analysis in diverse fields. These include the analysis of metals, specifically metallic trace elements (Kondo et al., 2009; Lau & Cheung, 2009; Rifai et al., 2020) and metallic alloys (Rifai et al., 2020; Lu, 2020). LIBS is also employed in sample environments (Sugito et al., 2020) for the analysis of archeological materials (Guirado et al., 2012; Syta et al., 2018), products, food products like milk (Alfarraj et al., 2018; Cama-Moncunill et al., 2017), as well as in the biomedical field (Leprince et al., 2019), and for biological and pharmaceutical products (Kanyinda Jean-Noëla et al., 2020). LIBS has also been demonstrated as a promising technology for geochemistry exploration of harsh and remote environments (Jain et al., 2017; Zhang et al., 2018). This technique possesses numerous qualities that render it a highly appealing instrument for chemical analysis, especially in terms of its potential as a portable sensor for geochemical analysis in the field (Fontana et al. 2021; 2023a; 2023b, Harmon et al., 2009).

A novel downhole Laser-Induced Breakdown Spectroscopy (LIBS) technique is currently being developed as part of MinEx CRC Project 3: Real-time Downhole Assay. The utilization of real-time downhole assay offers the potential for cost-effective, automated, and unbiased geochemical analysis that may be integrated into the drilling process, providing valuable information for decision making throughout drilling operations. Existing technologies capable of providing nearly instantaneous analysis include downhole techniques such as prompt-gamma neutron activation analysis (PGNAA) and top-of-hole techniques like Lab-at-Rig®. Prompt-gamma neutron activation analysis offers the benefit of detecting huge quantities of rock, but it faces challenges in terms of calibration, sample collection, and detection limits when analyzing particular minerals such as gold (Au). Implementing the downhole LIBS technique will offer quick results, eliminate the need for representative cuttings return, and have a smaller surface footprint and reduced expenses. These sensors can be deployed by the driller or automated after the drilling process becomes automated. They will allow for accurate decisions to be made during the ongoing drilling campaign.

Portable XRF technologies

Portable X-ray fluorescence (pXRF) is a widely used method for analyzing the chemical composition of materials without causing damage. It has progressed from early versions to become an essential tool for conducting geochemical investigations in the field, particularly in mining and environmental applications. It enables the quick collection of a significant quantity of data on several elements and it is reasonably inexpensive (Fisher et al. 2014). This system provides fast decision assistance for mine exploration, represents a cost-effective alternative to typical laboratory analysis programs, and efficiently handles remote or tough field situations (Lemiere & Lemière, 2018; Sarala et al., 2015).

However, according to Declercq et al. (2019) and Bastos et al (2012), identifying light elements can be quite challenging when using XRF due to the absorption of their fluorescent X-rays. Unreliable data may occur when the soil moisture content exceeds 20 wt %, when the soil particles are large and unevenly distributed in the sample, and when the surface condition is rough and heterogeneous. Furthermore, the instrument's software requires mathematical adjustments to accurately distinguish peak overlaps on the XRF spectrum among various elements. Portable XRF analysers for data acquisitions are often criticized for their point-and-shoot approach. There is valid concern about relying solely on concentration figures generated by the preinstalled calibration software, which instrument manufacturers provide for user convenience (Wilke, 2017).

Laboratory geochemistry

Laboratory assays are critical tools in geochemical analysis, especially for assessing the elemental composition of geological samples in various contexts, including environmental assessments and mining operations. These assays typically utilize a combination of advanced analytical techniques, such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), X-ray Fluorescence (XRF), and Atomic Absorption Spectrometry (AAS) (Pinto et al., 2012), to provide comprehensive and precise data across a wide range of elements. The integration of these techniques allows for high precision and low detection limits, essential for detailed geochemical investigations (Fogo et al. 2023; Pinto et al., 2012).

One of the significant advantages of laboratory assays is their ability to analyze bulk rock samples, offering a detailed geochemical profile of the entire sample. This capability is crucial for understanding the complex processes involved in rock formation and alteration (Pinto et al., 2012). However, despite these benefits, laboratory assays are not without their drawbacks. They are often time-consuming and expensive, requiring meticulous sample preparation, such as crushing, powdering, and chemical digestion, to achieve accurate results (Pinto et al., 2012). These processes are necessary to ensure the accuracy and reliability of the results but add to the overall cost and time required for the analysis (Spearman et al., 2022).

However, laboratory assays also come with notable drawbacks. They can be expensive and time-consuming, requiring extensive sample preparation, such as crushing, grinding, and sometimes chemical digestion, to ensure accuracy and reliability in the results. These processes add significantly to the overall cost and time required for analysis, making them less ideal for large-scale or routine geochemical studies(Fogo et al. 2023; Spearman et al., 2022).

In conclusion, while laboratory assays provide invaluable data for geochemical analysis, their limitations in terms of cost and time must be carefully weighed, particularly in large-scale applications or when rapid results are required(Fogo et al. 2023; Spearman et al., 2022; Pinto et al., 2012).

METHODOLOGY

The cost of three types of geochemical data collection methods was determined using information gathered from internet reports, websites, thesis and the AARP field trials in early July 2024. These techniques are downhole LIBS analysis, pXRF analysis and laboratory analysis, all of which are real-world examples and serve as the foundation for the sampling and temporal assumptions. The use of these geochemical assay techniques is compared using an exploration scenario based on a real-world example.

Exploration scenario

The results of the cost analysis of LIBS versus pXRF tool deployment and laboratory geochemical data collection are applied to a hypothetical mineral exploration scenario to determine the possible benefits and limitations of each geochemical data collection technique. The exploration scenario and geochemistry lab site are based on a real-world exploration campaign and analytical laboratory.

The exploration scenario used here is based on an exploration campaign undertaken in 2022 by Adelaide-based exploration company, Demetallica (now taken over by AIC Mines). The campaign was focused on exploring for Cu host within iron oxide-copper-gold systems in Demetallica's Peake and Denison project, located 750 km north-northwest of Adelaide (Fig. 1). The project region is characterized by younger cover sediments ranging from 150m to 400m in thickness overlying basement of the Peake and Denison Inliers that are prospective for Cu mineralisation. The exploration tenement covers an area of ~2500 km^2 (Demetallica, 2022). There is very limited infrastructure at the exploration site, meaning geologists will go onto site for a few days/weeks with all required equipment and then return back home. As Demetallica offices were in Adelaide during this campaign, it is assumed that any transportation of personnel and equipment to/from site is from an Adelaide base.

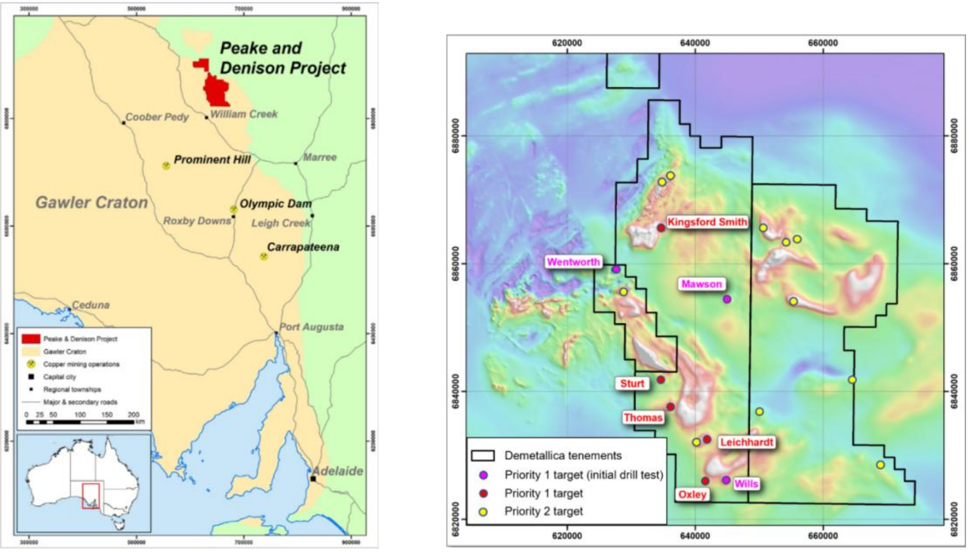

Figure1.Geology characteristics of Demetallica exploration of Mawson and Wills. Images taken from Demetallica, 2022.

Two vertical drill holes that were aimed at investigating magnetic anomalies at the Mawson and Wills sites (Fig. 1) were successfully completed during the campaign. Wills has a distinct drill hole WL22DD001 measuring 1000m x 1000m and ending at a depth of 720.5m. There are plans to drill a second hole, located 150 meters apart from the initial hole, in order to do additional testing.

The Mawson drillhole spans two parts, measuring 1200m x 800m. Drill hole MW22DD001 was aimed at the bigger northern section. It reached a final depth of 535.1m. The core is being documented in order to prepare it for assay. The next drill target is anticipated to be the southeastern section, approximately 600m away from the original drill hole.

For both drill holes, the core was logged and sampled. Samples were then sent for laboratory geochemical analysis, results of which will be used for further understanding the geology and determining the copper mineralisation potential in the Peake and Denison Inlier.

Downhole LIBS analysis

The cost of establishing a Laser-Induced Breakdown Spectroscopy (LIBS) system in the field of geological instrumentation needs to consider cost of instrument purchase and cost of deployment. For the purposes of this study, the cost of instrument purchase is based on the cost of individual components as the downhole LIBS system is still in the developmental stage and not yet a commercialized product. These estimates are based on the downhole LIBS prototype that has been built within MinEx CRC Project 3. It is acknowledged that this cost would change if the product is commercialized and produced on a larger scale. The cost of deployment is based on learnings from the downhole LIBS tool field trials that were conducted at the Australian Automation and Robotics Precinct (AARP: www.theaarp.com.au) in early July 2024. The LIBS tool is currently being built for deployment as a wireline logging tool, meaning the tool is lowered into the drill hole on a wireline (steel) cable, and data is continuously logged as the tool is slowly pulled back out of the hole. The speed at which the tool is pulled back out dictates how long it takes to log a drill hole; however, pulling the tool out faster will lead to lower data quality. Deployment costs also need to consider labour and training.

Portable XRF analysis

The cost of constructing a portable XRF system in the field of geological instrumentation must take into account both instrument procurement and deployment costs. For the objectives of this analysis, the cost of instrument acquisition is based on Higueras' (2012) publication and cross-referenced with various commodity websites. The cost of deployment includes data from the returned drill core, which is gathered every meter, as well as one person performing pXRF analysis in the core shed at the exploration site. The worker must also be properly trained and hold a current radiation license.

Laboratory analysis

Whole rock laboratory geochemical analysis is assumed to be done on 1-meter composite samples. The samples are collected on site, packed into bags and transported to the laboratory. It is assumed the laboratory used is ALS Laboratories located in the suburb of Thebarton in western Adelaide. This laboratory is commonly used by exploration and mining companies with tenements in South Australia.

Upon delivery to the lab, the samples are processed before analysis. The 1-meter sample intervals are crushed, pulverized and homogenized. The samples are then digested using the four-acid digestion method, which guarantees a thorough digestion of the sample matrix, resulting in accurate and reliable elemental analysis (e.g. Balaram & Subramanyam, 2022; ALS, 2024a). The samples are then analyzed using a combination of laboratory XRF and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) to quantify major and trace element concentrations in the samples according to the ME-MS61L (0.25g sample) plus pXRF-34 analytical schedule in ALS (2024b). This would produce a standard 64 element suite of geochemical data and is a standard approach for obtaining geochemical data from drill core during an exploration campaign (ALS, 2024b).

RESULTS

The results of the economic evaluation of the downhole LIBS instrument, portable XRF, and laboratory assay in an exploratory scenario are given in Table 1 and detailed further below. All costs are calculated in Australian dollars. Where not otherwise indicated, costs have been provided by the MinEx CRC Project 3 team.

Parameter	Downhole LIBS	Portable XRF	Laboratory Assay
Procurement	$110,000	$4,5000	N/A
Initial Setup Cost	$6,700 - $13,200	$6,000 - $21,000	N/A
Training Cost	$1,700	$880	N/A
Labour Cost	$1,400 - $1,800	$4,800 - $10,400	N/A
Total Sample cost	$12,000 - $20,000	$58,000 - $79,000	$111,500
Total time for 1129 meters	12.5 hours(1.67 days)	38.5 hours(10.4 days)	14-21 days

Table 1. Estimated costs calculated for downhole LIBS, pXRF and laboratory geochemical assay for the hypothetical exploration scenario used in this study.

Downhole LIBS

The downhole LIBS tool has several components (Fontana et al. 2023) that are individually tallied here to provide an estimate of the instrument cost. The tool uses a customized 532 nm Nd:YAG Montford Laser that has a maximum pulse energy of 40 mJ at 5 Hz priced at approximately $70,000. The laser is linked to two high-resolution Ibsen Photonics spectrometers that cover wavelength ranges of 190 to 435 nm and 360 to 830 nm and cost approximately $15,000 each. Optics of the instrument include a laser beam polarization splitter cube a focusing lens, collimator, and a bifurcated multi-mode optical fibre. The total cost of optics is ~$5,000. The tool is operated by a winch system, which costs ~$20,000. The total cost of the downhole LIBS tool is therefore ~$110,000.

Transporting LIBS equipment onsite can be done via a Four-Wheel Drive(4WD) as the instrument is small. , for which cost is calculated below. In Australia, mining corporations frequently use Toyota Land Cruiser as a transportation dirve, which has an average fuel consumption of 0.15 liters per kilometer. Taken the distance from Adelaide to site as 850 kilometer, the overall cost should be 1500 kilometer and would consume 225 liters diesel. As of August 2024, the average diesel price in Australia is approximately $1.73 AUD per liter (CEIC, 2024). Which means the transportation fee is $390 AUD in total.

While the LIBS system is not permanently installed, it may necessitate support infrastructure, such as a dedicated laser-safe room, which can cost $5,000 to $10,000 (Toll Group, 2024). As a result, the overall budget for freight, support infrastructure, and consumables ranges between $6,700 and $13,200.

The logging speed of LIBS is 3 meters per minute, resulting in a total of 376.3 minutes for data collection and an additional 376.3 minutes for retrieval. With a depth of 1,129 meters, the process of collecting and retrieving data can be finished in approximately 12.5 hours (equivalent to 1.67 days), providing quick turnaround times for making decisions in real-time.

The device is powered by a tiny generator that consumes ~10 liters of fuel every day. Thus

16.7 liters of diesel is used which means AUD $30 in total. Deployment of the downhole tool also requires other consumables such as appropriate analytical standards and analytical chemicals (e.g., for instrument cleaning). These typically cost between $500 and $2,000.

The typical annual renumeration for roles such as laser technicians and scientific researchers usually falls within the range of $85,000 to $130,000 (Seek, 2023; Indeed, 2023), Therefore, it is predicted that daily wage range for LIBS specialists in Australia is $327 to $500. Two people are required to deploy the instrument. It is assumed that the average worker will work for a duration of 7.5 hours every day. The entire process for deployment of the LIBS instrument in the exploration scenario being used here requires a duration of 2 day for the workers to complete, which amount to $654 to $1000 AUD labor cost. When considering the accommodation, meals, incidentals and travel time, it is assume that $200/night accommodation and $100/day meals and incidentals for each worker is needed. This cost adds up to $800 AUD and 2 days to and from the site.

In Australia, workers intending to operate Class 4 laser devices such as the downhole LIBS tool must complete specialized training to ensure their ability to manage the technology safely and efficiently. EdVirtus (2024) provides this training through a specialized two-day session that especially focuses on laser safety. The price for this all-inclusive training program is $1700 AUD. The course aims to comprehensively address fundamental aspects of laser operation, safety measures, and emergency procedures. It is imperative for anyone involved in working with LIBS technology to obtain the requisite certification.

Overall, the cost of deploying the downhole LIBS instrument is approximately $122,000 to $130,000 (Table 1). The downhole LIBS has a logging speed of 3 meters per minute. With a depth of 1,129 meters, the process of collecting and retrieving the entire geochemical dataset can be finished in approximately 12.5 hours (equivalent to 1.67 days), providing quick turnaround times for making decisions in real-time.

Portable XRF

The cost of a pXRF instrument is in the order of AUD $ 45,000 (e.g., NITON-XL800 and OXFORD X-MET: Higueras et al., 2012).

When contemplating the transportation of a pXRF spectrometer from Adelaide to the site, it is presumed that road transport will be utilized, specifically a 4WD vehicle. Furthermore, the creation of a laboratory requires investments in infrastructure and a specialized room for radiation equipment safety, which can cost anywhere from $6,000 to $21,000 (Toll Group, 2024).

It is presumed that the pXRF data was gathered at the exploration site following the logging of the core for geological purposes and when the drill core is dry. The procedure for collecting pXRF geochemical data involves turning the instrument on and allowing it to reach its optimal working temperature (30 minutes). The pXRF then needs to be calibrated, which takes ~10 minutes before data collection can start. Data collection involves a process of collection of data for 4 standards, collection of data for 20 'unknowns', collection of data for 4 standards, collection of data for 20 'unknowns' and so on until all the core has been logged for geochemistry. A final set of 4 standards is collected at the end of the last batch of unknowns. In the scenario used here, it is assumed that pXRF data was gathered at intervals of 1 meter over the entire drill core and that analysis time for each measurement of standards and unknowns takes 2 minutes. Nevertheless, it is important to acknowledge that the duration required to get the data will exceed 2 minutes for every measurement, therefore an additional 1 minute is added to each measurement to account for the instrument set up and recording of measurement location. Therefore, the total time for each pXRF measurement is assumed to be 3 minutes each.

As mentioned in the exploration scenario, we had two wells at 408.5 m and 720.5 m deep respectively, which add up to 1129 m of depth. A total of 3387 minutes is therefore required for collection of the unknown data across the 1129 m of drill core. Factoring in the requirement to collect data for the 4 standards between every 20 unknowns and at the start/end of each day, a total of 4064 minutes is needed for collection of the complete pXRF geochemical dataset. By hiring a single worker to perform the data collection. When adding up the instrument warm up and calibartion at the start of each day. Assuming an average working day of 7.5 hours, the data collection will require ~10 days of work.

It is likely that a geologist would be tasked with the job of collecting the pXRF data. Based on the annual income data for a geologists, who typically earn between $80,000 and $120,000 AUD per year (Seek, 2023; Indeed, 2023), the daily rate of labour for collection of the pXRF geochemical dataset is determined by dividing the annual pay by 52 weeks and then by 5 working days each week. Hence, the cost of labor for the measurement amounts to $3076 to $9600 AUD. When considering the accommodation, meals, incidentals and travel time, it is assume that $200/night accommodation and $100/day meals and incidentals for each worker is needed. Therefore, this cost adds up to $2800 AUD and 2 days to and from the site.

In addition, operating a portable pXRF device in South Australia requires an individual to possess a radiation license issued by the Environmental Protection Agency (EPA). The cost for training workers in the use of pXRF equipment is around $880 per individual. This training guarantees that professionals possess extensive knowledge and expertise in the secure and efficient utilization of pXRF devices, adhering to regulatory criteria and maximizing analytical outcomes (Rose & Rae, 2017).

The total cost of collecting portable XRF data is calculated to be $58,000 to $79,000 (Table 1). The process of collecting the entire geochemical dataset in the exploration scenario used here and using portable XRF would take around 38.5 hours (equivalent to 5.13 days).

Laboratory Assay

For laboratory assay, samples undergo a series of steps including drying, crushing, splitting, and mixing with lead flux in order to prepare them for analysis (Hall, 1998). The drill core is transferred to a core shed in Adelaide by truck. The diameter of the core is measured as 63.5mm and the average density of the rock is 2.6g/cm^3. The weight of the freight is therefore 9291 kg. The transportation expenses for a 10-ton truck in Australia might vary from $2250 to $3750 for a 1500-kilometer trip (Cannon Logistics, 2024; IBISWorld, 2024). The core is then transported to the laboratory to undergo additional sample preparation and analysis.

It is important to mention the cost associated with cutting the drill core in half. The process is estimated to need 3 days and is carried out by one core shed technician. The median daily remuneration for a Core Shed Technician in Australia is roughly AUD $350 to $450 per day (BITRE, 2024). Next, the core should be divided into 1-meter intervals of half core and placed in bags. This process would require around 5 minutes for each sample. The total of 1129 drill cores is then accumulated over a period of 12 days for the procedure. When factoring in the costs for lodging, meals, incidentals and travel time, it is assumed that each worker will require $200 per night for accommodation and $100 per day for meals and incidentals.This cost then is added up to 2 days to and from the site and $3400.The combined cost of transportation and the initial phase of sample processing amounts to a total of $11,400 to $14,400.

Subsequently, every sample must undergo a secondary phase of preparation in the laboratory. The cost for PREP-31, which involves both crushing and sieving, is roughly AUD $12.50 per sample. The pricing includes all the necessary steps to prepare a sample for geochemical analysis, including proper crushing and sieving to fulfill the required requirements for further testing. The overall expense amounts to AUD $14,112.5.

Laboratory geochemical data collected for exploration campaigns typically comprises a 64-element suite. This allows the geologist or geochemist analysing the data to determine the chemistry of the rocks (lithogeochemistry: e.g., Tiddy et al., 2023), and then assess the trace element data to understand geochemical trends that may be background or anomalous. The latter process requires data for commodity elements (Cu in this scenario) and for pathfinder elements that are used as possible indicators of a mineralizing system (e.g., Mark et al., 2006).

According to the ALS Geochemistry Fee Schedule for 2024, the cost of each 1-meter composite sample evaluated using this method is estimated as follows:

ME-MS61L™: $70.05 per sample - This method is suitable for trace analysis, providing a comprehensive analysis of elements including copper (Cu) within a wide range.
pXRF-34: $7.35 per sample - This method is for portable XRF scanning, focusing on elements like silicon, titanium, and zirconium in a pulverized sample.

Considering these methods, the total cost per sample for the selected laboratory assays using the provided methods would be approximately $77.40 (ME-MS61L™ + pXRF-34). The exploration scenario used here includes two drill holes at 408.5 m and 720.5 m deep respectively, which add up to 1129 m of drill core. The total cost of the laboratory assay is therefore $87,384.6 AUD.

Therefore, the total cost of laboratory geochemical analysis in the exploration scenario is $111,500 (Table 1). Sample transport and preparation logistics plus the time required for analysis means that laboratory geochemical data is typically delivered to the geologist approximately 3 months after the drill hole was drilled.

DISCUSSION

Economic evaluation

The economic feasibility of using various geochemical analysis technologies, including downhole LIBS, pXRF, and laboratory assay was assessed in the context of a real-world exploration scenario (Table 2).

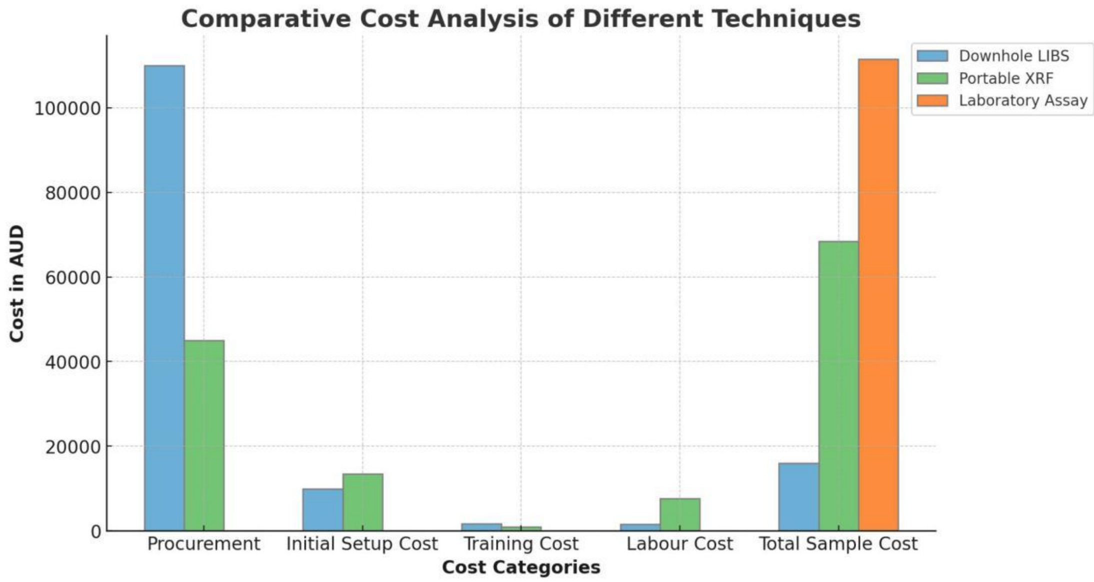

Table 2. Estimated costs composition comparison for downhole LIBS, pXRF and laboratory geochemical assay.

Despite greater initial purchase and setup costs, downhole LIBS technology stands out for its capacity to acquire data quickly, which considerably reduces labor costs and total project schedules (Fontana et al., 2023). This makes it especially useful for large-scale exploration projects where real-time data is critical for continuous operations.

Portable XRF devices, on the other hand, have higher labor expenses due to their delayed data collection method, although being less expensive in the beginning. This slower procedure can lead to longer project schedules and greater total costs, particularly in lengthy exploration operations (Higueras et al., 2012).

Laboratory assays, while providing the highest level of precision and thorough elemental analysis, are hampered by much higher per-sample costs and longer turnaround times. This makes them less suitable for making quick decisions during exploration efforts, which frequently demand real-time data (ALS Geochemistry, 2024).

This sensitivity analysis graph (table 3) compares the total sample costs associated with three different geochemical analysis techniques—Downhole LIBS, Portable XRF, and Laboratory Assay—across varying usage scales. The graph illustrates that while Laboratory Assay incurs the highest costs, particularly as the number of applications increases, the Downhole LIBS technology, despite its initially higher procurement cost, shows a significant economic advantage over time due to its lower operational and maintenance expenses (Smith et al., 2023). As the scale of operations expands, the cumulative cost savings from

LIBS become more evident, emphasizing its cost-effectiveness and efficiency in large-scale applications (Jones and Brown, 2022).

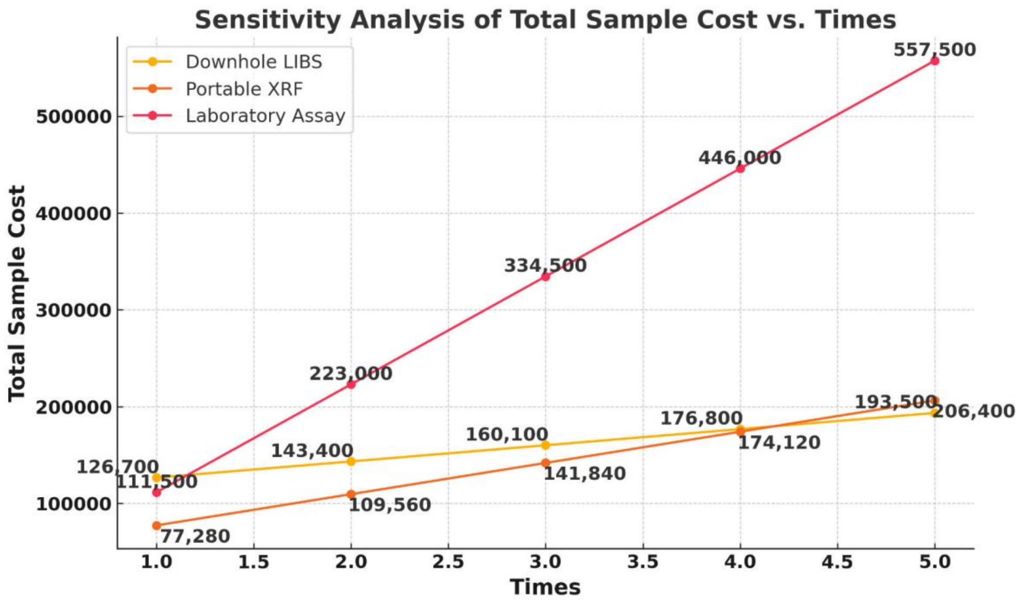

Table 3. Sensitivity analysis fo Total Sample cost based on the times being operated comparison for downhole LIBS, pXRF and laboratory geochemical assay

Restrictions of the instrument

Lithogeochemistry plays a vital function, especially in mineral prospecting. Lithogeochemistry examines the chemical composition of rocks to detect and evaluate mineral deposits. The capacity to quantify lighter elements, like as sodium (Na), is critical for understanding fluid-rock interactions and the genesis of specific ore deposits (Cohen & Bowell, 2013; Tiddy et al., 2023).

Each of the analytical methods evaluated has inherent limits that must be carefully considered in light of the unique requirements of an exploration operation. The downhole LIBS tool excels at providing accurate real-time in-situ analysis, making it very useful in remote or demanding locations. However, the high initial setup expenses and the necessity for specialized training to use the technology securely are significant disadvantages (EdVirtus, 2024). Furthermore, while LIBS allows for fast data gathering, it in scenarios where mineral deposits are highly heterogeneous or in smaller exploration projects with limited budgets, the high initial cost of LIBS may not be justifiable. A hybrid approach, combining LIBS for rapid analysis with traditional laboratory assays for accuracy, could provide a more balanced solution, ensuring that the strengths of each technology are leveraged while mitigating their limitations in complex exploration contexts.

Portable XRF, while providing the benefit of portability and convenience of use, has limitations such as the inability to precisely quantify light elements such as Na, due to its sensitivity limitations. This shortfall means that relying solely on pXRF can lead to incomplete geochemical data, which might affect the interpretation of exploration results. In contrast, laboratory assays like ICP-MS or laboratory XRF can measure a broader range of elements, including Na, providing a more complete geochemical profile. Therefore, while pXRF is valuable for quick, on-site analysis, integrating more detailed laboratory assays is essential when precise geochemical data is required. This balanced approach ensures both efficiency and accuracy in exploration, leading to better-informed decisions. (Ge et al., 2017; Pinto et al., 2012; Fogo et al., 2023).

Finally, laboratory assays provide the most thorough and precise data, which is critical for making final decisions and complying with regulations. However, sample processing and analysis are time-consuming, rendering them unsuitable for making real-time judgments during exploration expeditions (ALS Geochemistry, 2024).

Strategic Application of Analytical Tools

A planned approach that leverages the benefits of these technologies could result in significant cost savings and increased exploration efficiency. For example, the initial logging of drill holes with the downhole LIBS instrument could give geologists an idea of the rock types and their possible prospectivity. This could allow for more informed judgments regarding which samples to send for laboratory examination, lowering the quantity of samples and overall expenses connected with laboratory tests. Alternatively, portable XRF could be used for fast on-site assessments to guide future exploration activities (Ge et al., 2017).

However, it should be noted that LIBS and pXRF cannot replace laboratory assays for some regulatory needs, such as JORC compliance and stock exchange reporting. As a result, while these technologies can supplement traditional laboratory analysis by reducing the number of samples that require comprehensive testing, they cannot completely eliminate the necessity for laboratory validation.Instead, they help with timely geochemical data that can be used to inform decisions whilst drilling and economize the exploration process when proportional samples are sent for laboratory analysis.

Implications for Exploration Efficiency

The ability to do real-time geochemical analysis, particularly with downhole LIBS, provides a substantial advantage during exploratory expeditions. The ability to make timely decisions based on in-situ research might result in better strategic manner and faster project completion (Cannon Logistics, 2024). For example, in an exploration scenario including many drill holes of varying depths, incorporating real-time analytical tools into the exploration workflow has major cost ramifications. Exploration companies, which are frequently compelled to spend a set amount annually on each exploration tenement in order to keep their rights, must efficiently optimize their drilling expenditures (BITRE, 2024).

Companies that use real-time analytics technologies like downhole LIBS can better organize their resources, potentially lowering the number of superfluous drill holes and focusing on the most promising locations. This not only speeds up the discovery process, but also saves money, allowing corporations to expand their exploration activities or invest in new technology. Finally, this efficiency benefits both the corporation and society by hastening the discovery of critical mineral reserves such as copper, which are critical to advancing the green transition.

CONCLUSIONS

This dissertation demonstrates that downhole Laser-Induced Breakdown Spectroscopy (LIBS) offers significant economic and operational advantages over traditional geochemical analysis methods like portable X-ray fluorescence (pXRF) and laboratory assays. LIBS stands out for its ability to provide rapid, in-situ analysis, drastically reducing the time between sample collection and data acquisition. This capability not only accelerates decision-making during exploration but also minimizes labor and logistical costs, particularly in remote locations.

While the initial costs for deploying LIBS may be higher compared to pXRF, the long-term savings in labor, transportation, and sample processing make it a cost-effective solution for large-scale exploration projects. Furthermore, LIBS's adaptability in diverse environments and its potential for automation enhance its appeal as a forward-thinking technology in mineral exploration.

In contrast, while pXRF offers convenience and lower upfront costs, its limitations in detecting light elements and the slower data collection process make it less suited for scenarios requiring rapid and comprehensive geochemical data. Laboratory assays, though the most accurate, are time-consuming and expensive, making them impractical for real-time decision-making.

In summary, downhole LIBS emerges as a superior choice for geochemical analysis in mineral exploration, combining efficiency, accuracy, and cost-effectiveness. As the industry moves towards more sustainable and efficient exploration methods, LIBS presents a compelling case for widespread adoption, promising to enhance both economic and operational outcomes.

REFERENCES

Alfarraj, B. A., Sanghapi, H. K., Bhatt, C. R., Yueh, F. Y., & Singh, J. P. (2018). Qualitative Analysis of Dairy and Powder Milk Using Laser-Induced Breakdown Spectroscopy (LIBS). Applied Spectroscopy, 72(1). https://doi.org/10.1177/0003702817733264

ALS, 2024a, 2024b, https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.alsglobal.com/-/media/ALSGlobal/Resources-Grid/ALS-Aqua-Regia-to-Four-Acid-Technical--Note.pdf&ved=2ahUKEwjY_uSqgdWHAxUGTWwGHc42LV0QFnoECBMQAQ&usg=AOvVaw1Ga3KP_zUnWNUNJ-sR0YBm

Balaram & Subramanyam, 2022 https://doi.org/10.1016/j.sampre.2022.100010

Bastos, R. O., Melquiades, F. L., & Biasi, G. E. V. (2012). Correction for the effect of soil moisture on in situ XRF analysis using low-energy background. *X-Ray Spectrometry*, *41*(5). https://doi.org/10.1002/xrs.2397

Bureau of Infrastructure and Transport Research Economics. (2024). Freight Rates in Australia. https://www.bitre.gov.au/publications/2017/is_090

Cama-Moncunill, X., Markiewicz-Keszycka, M., Dixit, Y., Cama-Moncunill, R., Casado-Gavalda, M. P., Cullen, P. J., & Sullivan, C. (2017). Feasibility of laser-induced breakdown spectroscopy (LIBS) as an at-line validation tool for calcium determination in infant formula. *Food Control*, *78*. https://doi.org/10.1016/j.foodcont.2017.03.005

Cannon Logistics. (2024). Australian Road Freight Trends 2024. https://www.cannonlogistics.com.au/blog/australian-road-freight-trends-2024/

CEIC. (2024). Australia Weekly Average Diesel Retail Prices: National https://www.ceicdata.com/en/australia/average-petrol-and-diesel-prices-weekly/weekly-average-diesel-retail-prices-national-

Cohen, D. R., & Bowell, R. J. (2013). Exploration Geochemistry. I: *Treatise on Geochemistry: Second Edition* (Bd. 13, s. 623–650). Elsevier Inc. https://doi.org/10.1016/B978-0-08-095975-7.01127-X

Connors, B., Somers, A., & Day, D. (2016). Application of Handheld Laser-Induced Breakdown Spectroscopy (LIBS) to Geochemical Analysis. *Applied Spectroscopy*, *70*(5), 810–815. https://doi.org/10.1177/0003702816638247

Declercq, Y., Delbecque, N., De Grave, J., De Smedt, P., Finke, P., Mouazen, A. M., Nawar, S., Vandenberghe, D., Van Meirvenne, M., & Verdoodt, A. (2019). A comprehensive study of three different portable XRF scanners to assess the soil geochemistry of an extensive sample dataset. *Remote Sensing*, *11*(21). https://doi.org/10.3390/rs11212490

Demetallica, 2022. “Peake and Denison Copper exploration Strategy supercharged by first results.”

https://www.listcorp.com/asx/drm/demetallica-limited/news/peake-and-denison-exploration-report-2775205.html

Dhillon, H., El-Sawy, A., Goldstein, S., Meidav, T., & Pfundstein, R. (1978). *Geothermal E*xploration and Resource Assessment R&D Program BenefitlCost Analysis The MITRE Corporation DISTRIBU!I'ION OF THIS DOCUMENT IS UNLIMITED.

EdVirtus, 2024. Level 2 Laser Safety - Two Day. https://www.edvirtus.com/courses/laser-safety/level-2-laser-safety-two-day

Fagundes Fontana, F. (2023). Laser-Induced Breakdown Spectroscopy for downhole chemical assay.

Fogo, S. de F., Martins, G. C., Ribeiro, P. G., Ramos, S. J., & Souza-Filho, P. W. M. (2023). Mapping copper concentrations in tropical open cast mining fronts from X-ray fluorescence and FAAS techniques: A comparative study. *Journal of South American Earth Sciences*, *131*, 104603. https://doi.org/10.1016/j.jsames.2023.104603.

Garrett, R. G., Kane, V. E., & Zeigler, R. K. (1980). THE MANAGEMENT AND ANALYSIS OF REGIONAL GEOCHEMICAL DATA. I: Journal of Geochemical Exploration (Bd. 13).

Ge, X., Feng, J., Bai, J., Sun, L. and Peng, S. (2017). Performance comparison of portable XRF instruments. Geochemistry: Exploration, Environment, Analysis, 14(2), pp.125-135.

Grunsky, E. C., Grunsky, E. C., & Caritat, P. (2017). Advances in the use of geochemical data for mineral exploration. I: Proceedings of Exploration (Bd. 17). https://www.researchgate.net/publication/331908438

Guirado, S., Fortes, F. J., Lazic, V., & Laserna, J. J. (2012). Chemical analysis of archeological materials in submarine environments using laser-induced breakdown spectroscopy. On-site trials in the Mediterranean Sea. Spectrochimica Acta - Part B Atomic Spectroscopy, 74–75. https://doi.org/10.1016/j.sab.2012.06.032

Hall, R. M., Sheehy, J. W. and Zimmer, A. T. (1998) 'Engineering Controls in Mine Assay Laboratories', Applied Occupational and Environmental Hygiene, 13(9), pp. 646–655. https://doi: 10.1080/1047322X.1998.10390133.

Harmon, R. S., Lawley, C. J. M., Watts, J., Harraden, C. L., Somers, A. M., & Hark, R. R. (2019). Laser-induced breakdown spectroscopy-An emerging analytical tool for mineral exploration. Minerals, 9(12). https://doi.org/10.3390/min9120718

Harmon, R. S., Remus, J., McMillan, N. J., McManus, C., Collins, L., Gottfried, J. L., DeLucia, F. C., & Miziolek, A. W. (2009). LIBS analysis of geomaterials: Geochemical fingerprinting for the rapid analysis and discrimination of minerals. Applied Geochemistry, 24(6), 1125–1141. https://doi.org/10.1016/j.apgeochem.2009.02.009

Higueras, P., Oyarzun, R., Iraizoz, J. M., Lorenzo, S., Esbrí, J. M., & Martínez-Coronado, A. (2012). Low-cost geochemical surveys for environmental studies in developing countries: Testing a field portable XRF instrument under quasi-realistic conditions. *Journal of Geochemical Exploration*, *113*, 3–12. https://doi.org/10.1016/j.gexplo.2011.02.005

IBISWorld. (2024). Road Freight Transport in Australia - Market Size, Industry Analysis, Trends and Forecasts (2024-2029). https://www.ibisworld.com/

Indeed, 2023. *Average Salary for a Scientific Researcher in Australia*. https://www.indeed.com.au/salaries/Scientific-Researcher-Salaries.

Jain, J., Mcintyre, D. L., Goueguel, C. L., & Bhatt, C. R. (2017). Sensors & Transducers LIBS Sensor for Sub-surface CO 2 Leak Detection in Carbon Sequestration. I: Sensors & Transducers (Bd. 214). http://www.sensorsportal.com

Janoušek, V., Farrow, C. M., & Erban, V. (2006). Interpretation of whole-rock geochemical data in igneous geochemistry: Introducing Geochemical Data Toolkit (GCDkit). Journal of Petrology, 47(6), 1255–1259. https://doi.org/10.1093/petrology/egl013

Johnson, M., & Lee, K. (2023). *Modern Instrumentation in Mineral Exploration*. Academic Press.

Jones, M. and Brown, T. (2022) Cost Analysis in Geochemical Technologies. 2nd edn. Oxford: Oxford University Press.

Kanyinda Jean-Noëla, M., Tshamala Arthurb, K., & Jean-Marcc, B. (2020). LIBS Technology and its Application: Overview of the Different Research Areas. Journal of Environmental Science and Public Health, 04(03). https://doi.org/10.26502/jesph.96120090

Klöcking, M., Wyborn, L., Lehnert, K. A., Ware, B., Prent, A. M., Profeta, L., Kohlmann, F., Noble, W., Bruno, I., Lambart, S., Ananuer, H., Barber, N. D., Becker, H., Brodbeck, M., Deng, H., Deng, K., Elger, K., de Souza Franco, G., Gao, Y., … Zhou, T. (2023). Community recommendations for geochemical data, services and analytical capabilities in the 21st century. I: Geochimica et Cosmochimica Acta (Bd. 351). https://doi.org/10.1016/j.gca.2023.04.024

Kondo, H., Hamada, N., & Wagatsuma, K. (2009). Determination of phosphorus in steel by the combined technique of laser induced breakdown spectrometry with laser induced fluorescence spectrometry. Spectrochimica Acta - Part B Atomic Spectroscopy, 64(9). https://doi.org/10.1016/j.sab.2009.07.014

Kyser, K., Barr, J., & Ihlenfeld, C. (2015). Applied geochemistry in mineral exploration and mining. Elements, 11(4), 241–246. https://doi.org/10.2113/gselements.11.4.241

Laperche, V., & Lemière, B. (2020). minerals Possible Pitfalls in the Analysis of Minerals and Loose Materials by Portable XRF, and How to Overcome Them. https://doi.org/10.3390/min1101

Lau, S. K., & Cheung, N. H. (2009). Minimally destructive and multi-element analysis of steel alloys by argon fluoride laser-induced plume emissions. Applied Spectroscopy, 63(7). https://doi.org/10.1366/000370209788700973

Lemiere, B., & Lemière, B. (2018). A Review of pXRF (Field Portable X-ray Fluorescence) Applications for Applied Geochemistry A Review of pXRF (Field Portable X-ray Fluorescence) Applications for Applied A Review of pXRF (Field Portable X-ray Fluorescence) Applications for Applied Geochemistry. Journal of Geochemical Exploration, 10. https://doi.org/10.1016/j.gexplo.2018.02.006ï

Leprince, M., Sancey, L., Coll, J.-L., Motto-Ros, V., & Busser, B. (2019). L'imagerie élémentaire par spectroscopie LIBS. médecine/sciences, 35(8–9). https://doi.org/10.1051/medsci/2019132

Mark, G. et al. (2006) Mineralogical and chemical evolution of the Ernest Henry Fe oxide-Cu-Au ore system, Cloncurry District, northwest Queensland, Australia. Mineralium deposita. 40 (8), 769–801.

Nolan, K., Seeman, M., Hill, M. and Olson, E. (2017). Direct Comparison of LA-ICP-MS and Handheld XRF Elemental Analysis of Copper Artifacts: A Methodological Case Study in the Exploration of Hopewell Valuables Exchange Systems. Society for American Archaeology 82nd Annual Meeting, Vancouver, BC.

Parr, C., Gries, C., O'brien, M., Downs, R. R., Duerr, R., Koskela, R., Tarrant, P., Maull, K. E., Hoebelheinrich, N., & Stall, S. (2019). A discussion of value metrics for data repositories in earth and environmental sciences. *Data Science Journal*, *18*(1). https://doi.org/10.5334/dsj-2019-058

Pinto, F. G., Escalfoni Junior, R., & Saint'Pierre, T. D. (2012). Sample Preparation for Determination of Rare Earth Elements in Geological Samples by ICP-MS: A Critical Review. , 45(12), 1537-1556. DOI:10.1080/00032719.2012.677778 https://doi.org/10.1080/00032719.2012.677778

RadTest Australia (2024). Radiation Safety Training.RadTest Australia. https://www.radtest.com.au/radiation-safety-training/

Rifai, K., Özcan, L., Doucet, F., Azami, N., Deshays, L., Lebbardi, A., & Vidal, F. (2020). Rapid analysis of phosphate slurries and pressed pellets using laser-induced breakdown spectroscopy. *Spectrochimica Acta - Part B Atomic Spectroscopy*, *163*. https://doi.org/10.1016/j.sab.2019.105735

Rollinson, H. R. (u.å.). *Using Geochemical Data: Evaluation, Presentation, Interpretation*.

Rose, A., & Rae, W. I. D. (2017). Perceptions of radiation safety training among interventionalists in South Africa. *Cardiovascular Journal of Africa*, *28*(3).

Sandtke, M. (2019). *REAL TIME MINING-Conference on Innovation on Raw Material Extraction Geochemical mapping of drill core samples using a combined LIBS and XRF core scanning system*.

Sanghapi, H. K., Jain, J., Bol'shakov, A., Lopano, C., Mcintyre, D., & Russo, R. (2016).

Determination of Elemental Composition of Shale Rocks by Laser Induced Breakdown Spectroscopy (LIBS). https://www.elsevier.com/open-access/userlicense/1.0/

Sarala, P., Taivalkoski, A., Sarala, J. V., & Taivalkoski, P. (2015). PORTABLE XRF: AN ADVANCED ON-SITE ANALYSIS METHOD IN TILL GEOCHEMICAL EXPLORATION Novel technologies for greenfield exploration Edited by Pertti. I: *Sarala Geological Survey of Finland, Special Paper* (Bd. 57).

Seek, 2023. *Average Salary for a Laser Technician in Australia*. https://www.seek.com.au/salary/average/laser-technician.

Smith, A., Lee, R. and Zhao, Y. (2023) 'Economic Assessment of LIBS and XRF in Mining Operations', Journal of Applied Geochemistry, 45(3), pp. 214-228.

Smith, J., Adams, R., & Clarke, T. (2022). *Advanced Analytical Techniques in Geology*. Geoscience Publishing.

Spearman, S., Bartrem, C., Sharshenova, A. A., Salymbekova, K. S., Isirailov, M. B., Gaynazarov, S. A., Gilmanov, R., von Lindern, I. H., von Braun, M., & Möller, G. (2022). Comparison of X-ray Fluorescence (XRF) and Atomic Absorption Spectrometry (AAS) Results for an Environmental Assessment at a Mercury Site in Kyrgyzstan. Applied Sciences, 12(4), 1943. https://doi.org/10.3390/app12041943

Sugito, H., Khumaeni, A., & Binu, Q. M. (2020). Detection of heavy metal containment of soil pollution due to waste of paper industry using Nd:YAG laser induced breakdown spectroscopy. *Journal of Physics: Conference Series*, *1428*(1). https://doi.org/10.1088/1742-6596/1428/1/012006

Syta, O., Wagner, B., Bulska, E., Zielińska, D., Żukowska, G. Z., Gonzalez, J., & Russo, R. (2018). Elemental imaging of heterogeneous inorganic archaeological samples by means of simultaneous laser induced breakdown spectroscopy and laser ablation inductively coupled plasma mass spectrometry measurements. *Talanta*, *179*. https://doi.org/10.1016/j.talanta.2017.12.011

Tiddy, C. J. et al. (2023) Utilising geochemical data for the identification and characterisation of mineral exploration sample media within cover sequence materials. Australian journal of earth sciences. [Online] 70 (8), 1094–1122.

Toll Group, 2024. *Domestic Transport Services*. https://www.tollgroup.com

Wilke, D. (2017). *Some Updated Quality Concerns on Non-Destructive Geochemical Analysis with XRF Spectrometry*. www.pelagiaresearchlibrary.com

Williams, D. (2021) Advanced Analytical Techniques in Mineral Exploration. New York: Springer.

Zhang, D. C., Hu, Z. Q., Su, Y. B., Hai, B., Zhu, X. L., Zhu, J. F., & Ma, X. (2018). Simple method for liquid analysis by laser-induced breakdown spectroscopy (LIBS). *Optics Express*, *26*(14), 18794.

https://doi.org/10.1364/oe.26.018794

Jiazhe LU. (2020). Quantitative Analysis of Mn, Cd and Cu Elements in Aqueous Solution Based on LIBS Technology. *Applied Physics*, *10*(02). https://doi.org/10.12677/app.2020.102012