Applied Mineralogy:
A Critical Review and 5-Year Plan for Its
Strategic Use within Teck

by

Nichola Ann McKay
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Faculty of Business Administration

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Abstract

A strategic business case analysis and five-year plan are presented here for the Teck Applied Mineralogy group in Trail, British Columbia. Applied mineralogy is a key technical competency for Teck Resources that adds value in the fields of process mineralogy supporting optimization at the mining operations, and in ore characterization supporting evaluation of greenfield and brownfield properties. This 2016-2020 business plan for the applied mineralogy group is cognisant of the current mining industry downturn and recommends only incremental increases in staffing and project budgets during the period. Importantly, the plan recommends improved positioning of the group within Teck to maximize its contributions and a focus on customer relationships and timely delivery of value to projects. It also recommends the development of strategic outsourcing partnerships with commercial providers of applied mineralogy, including development of QA/QC protocols, so that this service is well managed within the company as a whole. There are some key capital expenditures necessary for the group in the next five years, including the replacement of mineralogical instrumentation, but their timing can be managed to coincide with improving corporate economics.

Keywords: Applied mineralogy, strategy, alignment, outsourcing, technology.
As with all other things in my life, I dedicate this EMBA project to my husband Greg Davison. He has been an inspiration to me ever since we met on a geological field crew in Nova Scotia in 1980. His unconditional love, knack for finding humour in life (accompanied with an appropriate pun) and passion for the mining industry regardless of its ups and downs has always kept me strong, allowed me to ask questions and grow.

I would also like to acknowledge my father – Gordon Alexander McKay – my very first role model.
Acknowledgements

I would like to thank Teck Resources for the tremendous opportunity to participate in this mining-dedicated EMBA program. It spanned the period from spring 2008 to summer 2015 along with the significant ebbs and flows of the mining industry. The program was an opportunity for me to expand in a new direction and better understand the real drivers of the company and the industry.

I would like to acknowledge my Teck supervisors over this period, Andy Stradling, Dan Ashman and Rob Stephens, for allowing me this valuable time away from the office to participate in the courses.

Next – I need to thank the professors that taught the courses throughout the GDBA and MBA programs. The Profs were always of good humour and up to the unique challenges of teaching us mining people in our boots rather than the regular MBAs in their suits!! And they liked pub nights too. Of course, I had my favourite courses and my less favourite courses (AC…….G), but all were really valuable and have contributed to my career.

The student support group at SFU – Valerie Zuccolo and her crew – was first class. We Teck students were treated royally for the entire program – not like when I was last in university.

Finally, I want to thank my Teck GDAB & MBA colleagues & classmates. More than half of the benefit of the program was in the interactions with all of you. I will always remember the spirited discussions. Special thanks to my MBA study group - Cory Takanaka and Michael Schwartz. Cory saved my life one night when I was hit with a bad bout of the stomach flu. And Mike is from Toronto!!!

From ART - thanks to Doug McKay (not a relative!) and Mark Richards for all the support back at the office and for the long conversations during the drives to and from Cranbrook. Doug – you are an excellent driver!!!! And thanks for stopping at Tim’s!

Lots of great times and discussions!!
Table of Contents

Chapter 1. Introduction ................................................................. 1
  1.1. Applied Mineralogy .......................................................... 1
      1.1.1. Ore Characterization / Predictive Mineralogy .................. 2
      1.1.2. Geometallurgy ....................................................... 2
      1.1.3. Process Mineralogy ............................................... 4
      1.1.4. Forensic Mineralogy .............................................. 5
      1.1.5. Environmental Mineralology ................................... 5
  1.2. Applied Mineralogy Facilities ............................................ 5
  1.3. Teck Resources Applied Mineralogy Facility .......................... 8

Chapter 2. Internal Analysis - Review of the 2015 ART Applied Mineralogy Facility ......................................................... 11
  2.1. Mission Statement ......................................................... 11
  2.2. Business Model ............................................................ 11
  2.3. Facility ................................................................. 14
  2.4. Key Equipment .......................................................... 17
  2.5. Staffing ............................................................ 18
  2.6. Labour Relations ....................................................... 19
  2.7. Workflow and Workload ............................................... 20
  2.8. Productivity ........................................................... 21
  2.9. Outsourcing ............................................................ 23
      2.9.1. Advanced Mineralogy ........................................... 23
      2.9.2. Automated Mineralology ....................................... 24
  2.10. Project History ...................................................... 24

Chapter 3. External Analysis - Applied Mineralogy Industry Analysis .......... 27
  3.1. Value, Loss and Liability ............................................... 27
  3.2. Teck’s Mineralogy Requirements .................................... 30
      Terminal Stream Analysis ................................................. 31
      Benchmarking Surveys .................................................. 32
      Process Mineralogy ...................................................... 32
      Ore Characterization ................................................... 33
Environmental Mineralogy ........................................................................... 33
Petrography .................................................................................................. 33

3.3. Porter 5-Forces Industry Analysis .............................................................. 34
   Industry Competitors .................................................................................. 35
   Buyers ......................................................................................................... 36
   New Entrants ............................................................................................. 37
   Suppliers ..................................................................................................... 37
   Substitutes ................................................................................................. 38
   Complementors ....................................................................................... 39
   Regulators ............................................................................................... 39
   Summary .................................................................................................... 39

3.4. Tests for a Core Resource ....................................................................... 40
   Value .......................................................................................................... 40
   Rareness .................................................................................................... 40
   Inimitability .............................................................................................. 40
   Leverage .................................................................................................... 41

3.5. PESTLE Analysis .................................................................................... 41

3.6. Mineralogy Service Options .................................................................. 43
   3.6.1. Automated Mineralogy .................................................................. 43
   3.6.2. X-ray Diffraction Analysis .............................................................. 45
   3.6.3. Electron Microprobe Analysis ....................................................... 45
   3.6.4. Advanced Techniques ................................................................... 46
   3.6.5. Classical Mineralogy ..................................................................... 46

3.7. New Technologies ................................................................................... 47
   3.7.1. Sample Preparation ....................................................................... 47
         Robotic Sample Preparation ............................................................... 47
         Polishing and Grinding ....................................................................... 48
         Automated Instrument Loading ........................................................ 49
   3.7.2. Instrumentation ............................................................................. 49
         Tescan TIMA and Zeiss Mineralogic ................................................... 49
         Zeiss Xradia 520 X-ray Microscope .................................................. 49
   3.7.3. CoreSCAN / HyLogger ................................................................. 50

Chapter 4.  ART AM 5-Year Business Strategy ................................................. 51

4.1. Scenarios ................................................................................................ 51
   4.1.1. Scenario 1 – Out-source Mineralogical Testing ................................. 51
   4.1.2. Scenario 2 - Update and Expand the present ART AM facility to
         meet all of Teck’s requirements ......................................................... 56
   4.1.3. Scenario 3 – Update of Current Facility ............................................ 59
   4.1.4. Comments ..................................................................................... 61

4.2. ART AM – A 5-Year Plan ...................................................................... 61
   4.2.1. Scenario Analysis Review ............................................................... 61
   4.2.2. 5 Year AM Budget ......................................................................... 62
   4.2.3. Projects and Technical Focus .......................................................... 63
   4.2.4. Capex ............................................................................................ 64
   4.2.5. Opex .............................................................................................. 64
   4.2.6. Alignment ...................................................................................... 65
Chapter 5. Recommendations ................................................................. 66

References 68
Appendix A. Automated Sample Preparation ........................................ 70
  FLSmidth® QCX/RoboLab® ................................................................. 70
  Buehler Vanguard 2000 .................................................................. 70
  Struers Hexamatic ......................................................................... 71
Appendix B. Automated Mineralogy ..................................................... 72
  FEI: QemSCAN – Quantitative Evaluation of Minerals using Scanning    
    Electron Microscopy ................................................................. 72
  FEI: MLA - Mineral Liberation Analyzer .......................................... 72
  MLA Express ............................................................................. 73
  Tescan: TIMA™ Mineral Analyzer .................................................. 74
  Tescan: TIMA™ Mineral Analyzer – Automated Loading System ......... 74
  Zeiss: Mineralogic Mining .......................................................... 75
Appendix C. Other Mineralogical Instruments ...................................... 77
  Panalytical - XPert3 Powder ......................................................... 77
  Bruker – D8 / D8 Advanced ............................................................ 77
  Rigaku – UltimaIV ..................................................................... 78
  Zeiss - Xradia 520 Versa .............................................................. 79
  Bruker Skyscan ......................................................................... 79
  CoreSCAN MarkIII ..................................................................... 80
  HyLogger .................................................................................. 81
List of Tables

Table 1-1  Key Applied Mineralogy Instrumentation .......................................................... 6
Table 2-1  2015 AM Group Project Budget........................................................................ 13
Table 2-2  Comparison of Project Costs between ART and Commercial Laboratories .......................................................... 14
Table 2-3  Key Instruments and Laboratory Equipment....................................................... 14
Table 2-4  Replacement price for key instruments and equipment in the ART AM Facility. ................................................................................... 17
Table 2-5  SWOT Analysis for ART AM Facility................................................................. 26
Table 3-1  Projected Annual Requirements for Applied Mineralogy............................... 30
Table 3-2  PESTLE Analysis of Applied Mineralogy at ART ........................................... 42
Table 3-3  List of significant commercial facilities offering automated mineralogy services. ................................................................................... 44
Table 3-4  List of Canadian universities with automated mineralogy capacity. .......... 45
Table 3-5  List of Canadian government research facilities offering electron microprobe analysis. ................................................................................... 46
Table 4-1  Projected 5 Year Budget and Costs for the AM Group ................................. 63
List of Figures

Figure 1-1  The Mining Cycle. The cycle ranges from the exploration stage to final project closure. ................................................................. 1
Figure 1-2  An example of a geomet block model. Colours represent modelled zinc recovery in the Red Dog Aqqaluk Pit. ...................... 3
Figure 1-3  Mineralogically limiting grade-recovery relationship for a theoretical copper plant feed grading 0.5% Cu and containing chalcopyrite................................................................. 4
Figure 2-1  Simplified organizational chart showing the reporting line for Applied Mineralogy and the relationship to its Teck customers........ 12
Figure 2-2  ART facility showing location of AM offices and laboratory area.......... 16
Figure 2-3  ART Applied Mineralogy Historical Staffing Levels. ................... 19
Figure 2-4  Workflow Diagram for Mineralogical Study of Metallurgical Products. ................................................................................. 21
Figure 2-5  2014 AM Instrument Utilization....................................................... 22
Figure 2-6  ART Mineralogy Project History by Commodity based on polished sections analysed......................................................... 25
Figure 2-7  ART Mineralogy Project History by Site or Project based on number of polished sections analysed.......................................... 25
Figure 3-1  Prospect Theory and its relationship to decision making. Opportunity losses are shown as black arrows........................... 30
Figure 3-2  Five Forces diagram showing major factors impacting the Applied Mineralogy industry from the perspective of a mining company........ 35
Figure 4-1  Key factors to consider for a decision to outsource. ................. 52
Figure 4-2  Spider plot showing relative position ART AM and commercial testing for five key outsourcing considerations. ..................... 53
Figure 4-3  Spider plot showing relative position of strengths and weaknesses for ART AM vs. Commercial Laboratory. ............................ 54
Figure 4-4  5-Year Breakdown of AM Facility Development ....................... 63
Figure 4-5  Revised organization structure showing optimal placement of AM. ...... 65
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AM</td>
<td>Applied Mineralogy</td>
</tr>
<tr>
<td>ART</td>
<td>Applied Research &amp; Technology</td>
</tr>
<tr>
<td>BU</td>
<td>Business Unit</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive Spectrometer or Spectrometry</td>
</tr>
<tr>
<td>GFC</td>
<td>Global Financial Crisis</td>
</tr>
<tr>
<td>LOM</td>
<td>Life of Mine</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-government Organization</td>
</tr>
<tr>
<td>MLA</td>
<td>Mineral Liberation Analyser or Analysis</td>
</tr>
<tr>
<td>PGM</td>
<td>Platinum Group Mineral</td>
</tr>
<tr>
<td>POR</td>
<td>Person on Roll</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SFU</td>
<td>Simon Fraser University</td>
</tr>
<tr>
<td>WDS</td>
<td>Wavelength Dispersive Spectrometer or Spectrometry</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray Diffraction Analyser or Analysis</td>
</tr>
</tbody>
</table>
Executive Summary

Applied mineralogy (AM) is a specialized form of analysis that characterizes minerals in ore and metallurgical products with a focus on mineral beneficiation, and can also extend to the study of synthetic or secondary products such as smelter slags and mattes. Teck Resources has an AM laboratory located at the Applied Research & Technology (ART) facility in Trail, British Columbia that was founded in late 2003 to support ore characterization and concentrator optimization strategies for Teck mining operations and projects.

The ART AM technical facilities consist of several sample preparation laboratories, optical microscopes and advanced instrumentation including an X-ray diffractometer (XRD) and two Mineral Liberation Analysers (MLAs). Technical projects in the past 10 years have spanned most of Teck’s operations and the group has developed expertise in copper, zinc, lead, gold, PGM, nickel and coal mineralogy. In May 2015, the AM group comprises 2 full-time mineralogists, 1 part-time mineralogist and three technicians. The ART AM budget for 2015 is $1.3M and comprises project work for the Zinc, Copper and Coal Business Units. Teck Resources utilizes an estimated $2.5M worth of applied mineralogical testing annually, largely for the base metal operations. ART AM completes approximately one-half of this work and has developed strong relationships with many sites.

Since the commissioning of the AM facility in 2003, there has been a large expansion of commercially available mineralogical services. This, together with the current prolonged mining industry downturn, has produced significant external accessibility and lower prices. In the past year, and due in large part to the current economic downturn, the ART budget has been reduced and AM staffing levels further reduced by two persons thereby hampering the ability of the group to meet its time-dependent project commitments.

A business analysis of the applied mineralogy testing industry clearly shows that ART AM is strongly impacted by the growth in availability and technical capacity of the commercial service providers, by the ability of ART’s Teck customers to select from
several contract facilities based on quality, cost and turnaround, by the high cost for ART AM to upgrade and streamline their current facility, and by the need for continued support of Teck Corporate to supply OPEX and CAPEX for the AM facility.

Three scenarios were explored for ART AM as a business plan for the next 5 years. Scenario 1 proposed full outsourcing of applied mineralogy testing to take advantage of the large capacity and excellent pricing available at commercial laboratories. It would improve capital efficiency and better focus the mineralogists and metallurgists to acquire and utilize mineralogical data to enhance project value. Scenario 2 proposed the expansion and upgrading of the ART AM facility to meet all of Teck’s requirements. This makes poor business sense, based on the large technical capacity currently available in the market and the present challenges of providing the requisite service at ART. The large Capex, Opex and logistical requirements of this scenario are especially non-attractive in the present cash-constrained mining economy. Scenario 3 proposed a re-alignment of the current ART AM business model to begin to develop strategic relationships with commercial service providers and manage the outsourcing of Teck’s project work, while continuing to have a small on-site instrument base, ideally upgraded when capital is available, for key projects, trouble-shooting and QA/QC. The mineralogists will increase their presence in Teck project teams, their utilization of large data sets and the evaluation of new technologies. Re-alignment of ART AM within Teck for better strategic position is strongly recommended. Scenario 3 is recommended as the best path forward for the next 5 years at ART, as it blends the business sense of strategic outsourcing, with the current ART AM business model where data is acquired for key projects, and causes the least disruption of the current work force. An ART AM budget and milestones for key capital expenditures are presented.

As a final note, this 5-year plan for ART AM is inexorably linked to the 5-year plan of ART itself, which is under development.
Chapter 1. Introduction

1.1. Applied Mineralology

Applied mineralogy (AM) is a specialized form of analysis that characterises minerals in ore and metallurgical products with a focus on mineral beneficiation, and can also extend to the study of synthetic or secondary products such as smelter slag and matte (Jones, 1987). Petruk (2000) defined Applied Mineralogy as the “application of mineralogical information to understanding and solving problems encountered during exploration and mining, and during processing of ores, concentrates, smelter products and related materials”.

Applied Mineralogy comprises a group of specialized testing functions, specifically Ore Characterization or Predictive Mineralogy with its application to Geometallurgy, Process Mineralogy, Forensic Mineralogy and Environmental Mineralogy. These testing types are applied at differing stages in the mining cycle as shown in Figure 1-1, beginning with mineral exploration and ultimately ending with mine closure.

Figure 1-1 The Mining Cycle. The cycle ranges from the exploration stage to final project closure.
1.1.1. **Ore Characterization / Predictive Mineralogy**

Ore characterization is the study of both the valuable and deleterious minerals in rock from greenfields (exploration) properties. Valuable minerals can consist of metal-bearing phases, such as sphalerite (ZnS) and galena (PbS), that will undergo further refinement to pure metal, or minerals of value in their natural state such as gemstones (diamond, corundum – ruby and sapphire), precious metals (native gold, silver or copper) or industrial minerals (garnet used for abrasives, gypsum used for building materials, graphite, barite and talc). Evaluation of the type of mineralization, its mineral associations and natural grain size (or liberation size) allows for prediction of potential beneficiation options and the range of quality of a future concentrate or product. Deleterious minerals comprise unwanted phases, such as those containing mercury, arsenic or cadmium, which would incur smelter penalties if collected into a concentrate, those that could cause environmental problems if released into the environment as dust or in discharge waters, or problematic minerals such as swelling clays which cause process problems in a flotation concentrator. Ore characterization also identifies the rock and alteration types and can point toward metal emplacement mechanisms which allow the exploration geologist to better understand the deposit thereby focusing their exploration efforts.

1.1.2. **Geometallurgy**

Geometallurgy is a relatively new discipline, and is defined here as the spatial modelling of relevant geological, geotechnical, mineralogical, geochemical and metallurgical attributes of an ore body and utilization of this data in economic analysis, mine planning, scheduling and processing. An example of a geomet model for the Aqqaluk pit at Red Dog is shown in Figure 1-2 (Bye, 2010). The distribution of colours, from blue to red, represents the predicted spatial variation of zinc recovery per ore block based on a combination of metallurgical and mineralogical testing. Geometallurgy has become recognized as a key process for unlocking the maximum value of a resource and in the reduction of operational risk (Vann et al., 2011). The development of automated mineralogical tools such as MLA and QemSCAN have allowed, for the first
time, the acquisition of and modelling of large quantities of mineralogical data consisting of bulk mineralogy, ore mineral speciation and deleterious phases.

Figure 1-2 An example of a geomet block model. Colours represent modelled zinc recovery in the Red Dog Aqqaluk Pit.
Adapted from Bye (2010).

One of the earliest applications of automated mineralogy to geometallurgical modelling was by Sutherland et al. (1989) who measured the Phase Specific Surface Area (PSSA), a proxy of mineral grain size, in lightly crushed Australian ores using a QemSCAN and related it to flotation recovery response and the Concentration Efficiency Index (CEI). More recently, Sciortino et al. (2013) of Royal Nickel used QemSCAN analysis to define metallurgical domains that explained recovery performance throughout the Dumont nickel deposit. At Dumont, nickel occurs within the sulphide minerals pentlandite ((Ni,Fe)$_9$S$_8$) and heazelwoodite (Ni$_3$S$_2$), the nickel-iron alloy awaruite (Ni$_{2.5}$Fe) and as a trace component within the silicate minerals serpentine and olivine. The understanding of the nickel distribution between these various minerals was critical to prediction of future flotation recoveries and concentrates grades, and could not be obtained solely using assay information. Mineralogical data also contributes to understanding of rheological behaviour and its impact on beneficiation (Lower et al., 2013). The use of mineralogical data to predict ore hardness is still in a developmental phase, but relationships to alteration style (Harbort et al., 2013) and texture (Ozarzun and Arevalo, 2011) have been identified.
1.1.3. Process Mineralogy

Process mineralogy is the classic study of mineral processing circuit feeds and resultant products, including concentrates and tailings. In process feeds, it is important to understand the nature of both the value and non-value minerals and their textural intergrowths. Using the newer automated mineralogical techniques, it is possible to generate a mineralogically limiting grade-recovery curve for a metal at a specific grind size. This curve shows the maximum possible concentrate grade and associated recovery at one extreme and the maximum possible metal recovery and associated concentrate grade at the other extreme (Figure 1-3).

![Figure 1-3 Mineralogically limiting grade-recovery relationship for a theoretical copper plant feed grading 0.5% Cu and containing chalcopyrite](image)

Mineralogical study of process tailing streams allows for characterization of the nature of metal losses and will point to potential plant activities, such as finer grinding or longer residence time, which could reduce these losses. Examination of process concentrates allows for characterization of the presence of diluent, or non-value minerals, and will point to potential plant optimization actions to reduce their quantity and improve concentrate grade. In the last 15 years, automated mineralogical techniques have allowed for mineralogical characterization of multiple plant streams collected during process plant survey campaigns (Lotter, 2011). Thus mineralogical insight, specifically the mineral composition and liberation across a range of size fractions, now has been
added to a process that previously could only use assay data to diagnose plant performance.

1.1.4. **Forensic Mineralogy**

Forensic Mineralogy is the application of mineralogical expertise to process failure analysis. Mineral processing plants and smelters regularly experience performance that is mildly to significantly out of specification. At these times, it is important to provide a rapid diagnosis of the condition in an attempt to solve the process problem. Delay in a diagnosis could result in large financial losses while processes provide substandard products or are halted.

1.1.5. **Environmental Mineralogy**

Environmental mineralogy is the application of mineralogical expertise to a wide variety of process products that can have an environmental impact, such as tailings, waste rock and dust. Environmental mineralogy is an expertise that is growing in importance as the impact of mining activities on local communities and the environment come under additional scrutiny.

1.2. **Applied Mineralogy Facilities**

Applied mineralogy laboratories exist within the corporate environment, at universities and government research facilities and at commercial laboratories that specialize in mining industry support. The laboratories are equipped with a wide range of specialized instrumentation, and staffed with technologists and scientists experienced in this form of analysis and the interpretation of the results. Specific instrumentation types and numbers vary depending on the requirements of the facility. Typical corporate and commercial laboratories contain one or more research-quality polarizing microscopes, also known as an ore or petrographic microscope, and stereoscopic microscopes that allow for examination of specimens at low to high magnification using incandescent light. They also have X-ray Diffractometers (XRD) and Scanning Electron Microscopes (SEMs) that are equipped to perform automated mineralogical analyses,
such as the Mineral Liberation Analyser (MLA), Quantitative Evaluation of Minerals using Scanning Electron Microscopy (QemSCAN) or TIMA. These systems use a combination of line or point scans, image analysis and X-ray analysis to identify and quantify mineral components based on a pre-defined library of mineral characteristics (Gu, 2003). The electron microprobe is another important component of the AM laboratory. This SEM-based instrument uses wavelength-dispersive spectrometry (WDS) for quantitative analysis and is able to achieve much lower elemental detection limits than the energy dispersive spectral analysis (EDS) technique used by MLA and QemSCAN systems.

There is a wide range of other instrumentation, including Dynamic SIMS, TOF-SIMS, TOF-LIMS, XPS and Auger microscopy that supplement the information obtained using the more standard suite of instrumentation described above. These tools are used to investigate even lower limits of elemental detection, the specific chemical form of an element and the elemental species present on mineral surfaces. These advanced instruments generally exist within the research-focused university or government laboratory environment as they are extremely expensive to acquire and technically complex to operate. A list of the key instrumentation used in an applied mineralogy laboratory is shown in Table 1-1.

Table 1-1  Key Applied Mineralogy instrumentation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Detail</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>binocular microscopy</td>
<td>Imaging of specimens</td>
<td>Textural &amp; phase study.</td>
</tr>
<tr>
<td>petrography</td>
<td>Study of rocks in thin section</td>
<td>Textural &amp; phase study. Rock &amp; mineral ID.</td>
</tr>
<tr>
<td>coal petrography</td>
<td>Study of coal macerals</td>
<td>Textural &amp; phase study.</td>
</tr>
<tr>
<td>ore microscopy</td>
<td>Analysis of minerals in reflected light</td>
<td>Textural &amp; phase study. Mineral ID</td>
</tr>
<tr>
<td>image analysis</td>
<td>Image analysis of minerals</td>
<td>Use of image analysis to identify and quantify rock and mineral textures</td>
</tr>
<tr>
<td>cathodoluminescence</td>
<td>analysis of mineral luminescence</td>
<td>Mineral compositional zoning and paragenesis.</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
<td>Imaging texture (Secondary) or composition (Backscatter).</td>
</tr>
<tr>
<td>Instrument</td>
<td>Detail</td>
<td>Application</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
<td>Molecular structural imaging.</td>
</tr>
<tr>
<td>Tomography</td>
<td>Computer Assisted Tomography (X-ray Microscopy - XRM)</td>
<td>Textural &amp; phase study.</td>
</tr>
<tr>
<td><strong>Mineral Phase ID</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray Diffraction</td>
<td>Qualitative crystalline phase ID. Various quantitative techniques.</td>
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<tr>
<td>Rietveld Analysis</td>
<td>Mineral quantification for XRD</td>
<td>Quantitative crystalline phase ID.</td>
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<tr>
<td>Synchrotron XRD</td>
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<td>High resolution phase analysis.</td>
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<tr>
<td>MicroXRD</td>
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<td>Fine particle phase ID.</td>
</tr>
<tr>
<td><strong>Automated Mineralogy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QemSCAN / MLA / TIMA</td>
<td>Mineral Liberation Analyzer &amp; other</td>
<td>Mineral Identification, quantification &amp; association.</td>
</tr>
<tr>
<td><strong>Mineral Chemistry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive Spectral Analysis</td>
<td>Quantitative element analysis.</td>
</tr>
<tr>
<td>WDS</td>
<td>Wavelength Dispersive Spectral Analysis - Electron Microprobe</td>
<td>Quantitative element analysis.</td>
</tr>
<tr>
<td>Dynamic SIMS</td>
<td>Secondary Ion Mass Spectrometry</td>
<td>Quantitative element analysis.</td>
</tr>
<tr>
<td>LAM-ICP-MS</td>
<td>Laser Ablation Inductively-Coupled Plasma Mass Spectrometry</td>
<td>Elemental and isotopic identification &amp; quantification.</td>
</tr>
<tr>
<td><strong>Surface Chemistry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AES</td>
<td>Auger Electron Microscopy</td>
<td>Elemental analysis of surfaces.</td>
</tr>
<tr>
<td>TOF-SIMS</td>
<td>Time of Flight SIMS</td>
<td>Elemental, ion and molecular analysis of surfaces.</td>
</tr>
<tr>
<td>XPS</td>
<td>X-ray Photoelectron Spectroscopy</td>
<td>Elemental, ion and molecular analysis of surfaces.</td>
</tr>
<tr>
<td><strong>Scanners / Sensors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIMA (SWIR)</td>
<td>Short wave infrared</td>
<td>Identification of hydrous minerals (micas, chlorites, clays).</td>
</tr>
<tr>
<td>Instrument</td>
<td>Detail</td>
<td>Application</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>IR</td>
<td>InfraRed</td>
<td>Identification of hydrous minerals.</td>
</tr>
<tr>
<td>CORESCAN</td>
<td>Hyperspectral logging</td>
<td>Spectral mapping of core.</td>
</tr>
<tr>
<td>Geotek Logger</td>
<td>Rack mounted imaging and geophysical tools</td>
<td>Imaging &amp; geophysical mapping of core.</td>
</tr>
<tr>
<td>HyLogger</td>
<td>Rack mounted short and thermal infrared logging</td>
<td>SWIR &amp; TIR mapping of core.</td>
</tr>
</tbody>
</table>

Recent technological advancements in imaging and sensing now allow deployment of AM instrumentation to the mine-site in the form of multi-spectral analysis of drill core (Corescan, 2014) and automated mineralogical analysis of daily concentrator streams (AXT, 2015).

This brief summary of the key applications of applied mineralogy to the mining industry demonstrates that AM is a key strategic technical discipline that provides information to a wide range of mining applications, can utilize a wide range of techniques, applies automated mineralogy techniques, such as MLA & QemSCAN, to provide large databases to deposit or process modelling and continues to integrate new techniques to solve mineral processing problems. It is technically advanced and growing in its application.

### 1.3. Teck Resources Applied Mineralogy Facility

Teck Resources has an AM laboratory located at the Applied Research & Technology (ART) facility in Trail, British Columbia. ART is a corporately-funded, internal support division that provides technical consultancy, project management, and laboratory or site-based testing for Teck’s mines and advanced project sites. ART’s technical capabilities are in mineral processing of base metals and coal, hydrometallurgy and pyrometallurgy, water treatment, environmental assessment and applied mineralogy. ART has been in existence in various forms for over 50 years. In its early years, the facility performed key development studies for the Trail Pb-Zn smelter and later for the mines that supplied the concentrates to the smelter, specifically the Sullivan Mine (British Columbia) and the Red Dog Mine (Alaska). In 2004, ART came under the
direction of corporate management and expanded its technical breadth to assist Teck’s gold, copper and coal mines, and more recently, the Fort Hills oil sands project.

The advanced AM laboratory at ART was founded in late 2003 to support ore characterization / geometallurgical projects and concentrator optimization strategies for Teck mining operations, specifically for the Red Dog Mine and Highland Valley Copper. There was an urgent need in 2003 for the Red Dog Mine to understand the ore processing characteristics of ore in its new Aqqaluk Pit, as the Main Pit would be depleted in 2011. In the past ten years, the technical capability of the AM team has grown to handle specific development projects at all of Teck properties, including projects from the Carmen de Andacollo copper mine and the Elk Valley coal mines.

ART AM technical facilities comprise: a lapidary preparation laboratory, binocular, ore and petrographic microscopes, and more advanced instrumentation including an X-ray diffractometer (XRD) and two Mineral Liberation Analysers (MLAs). The advanced instrumentation is now over 10 years old and will soon require replacement and upgrading. The group directly benefits from its collaboration with the on-site metallurgical laboratories and shares several sample preparation facilities. Staffing comprises technicians, applied mineralogists and mineral processing engineers, all of whom have a background in the characteristics and processing behaviours of the ores at Teck’s mines and advanced projects.

At the time of the 2003 ART AM lab installation, advanced instrumentation, such as the MLA or QemSCAN, was not widely available through commercial laboratories, and could only be supported within a private corporate facility. Teck’s AM facility followed the design of similar corporate labs of the time, such as the Falconbridge / X-strata (XPS) research lab in Sudbury Ontario, the Anglo American facility in Johannesburg, South Africa, the Rio Tinto facility in Melbourne, Australia and the Phelps Dodge facility in Safford, Arizona. Since that time, commercial laboratories such as SGS, ALS and ACME (BV) have equipped large capacity, advanced applied mineralogy laboratories in North and South America, Australia and South Africa. Gu et al. (2011) stated that there have been close to two hundred systems installed in the past 10 years. During this same ten years, corporate AM facilities came under increased scrutiny, with
several being closed, such as those of BHP's in Adelaide and Perth, and others placed on a partial or total cost-recovery business model, such as Glencore-Xstrata, Sudbury, and Barrick, Vancouver.

An important externality in this evaluation of the applied mineralogy group within Teck Resources is the reality that the mining industry is a cyclic entity, with periods of high metal prices, acquisitions and expansions and periods of low metal prices, cost-cutting and contraction. In 2015, the industry is currently in a prolonged 4-year downturn with historically low coal, iron ore and oil prices. This has created a realignment of corporate priorities within Teck and a sharp focus on cost-cutting, value creation and cash flow. In this environment, staffing levels are being reviewed closely and technical specialists are being redeployed to critical projects.

It is with this background of the technical field of applied mineralogy, its key applications, a brief discussion of the ART AM facility, and the market externalities, that an updated 5-year strategic plan is required for the ART AM facility, and is the subject of this document. The study will:

- review the ART AM facility
- examine the current business environment for applied mineralogy
- discuss new emerging technologies of interest
- provide a discussion of potential service models for ART AM
- make recommendations for ART AM 2016 – 2020
Chapter 2.

Internal Analysis - Review of the 2015 ART Applied Mineralogy Facility

2.1. Mission Statement

The Applied Mineralogy Group at ART provides mineralogical expertise to Teck Resources that adds economic value to ore characterization, process design, process optimization, forensic/process failure projects and environmental activities at mining operations, and within the corporate Exploration and Advanced Projects groups. It aims to be imbedded in key Teck teams that develop geological models, perform mine planning and process design, optimize metallurgical processes and solve process problems. It achieves results from the acquisition and interpretation of appropriate mineralogical data, primarily from the on-site laboratory in Trail, but also from collaboration with external sources such as commercial, university and government lab facilities, and by remaining current on the development of promising new technologies and their application to Teck’s operational and project needs.

2.2. Business Model

The Applied Mineralogy Group forms part of the Applied Research & Technology Group located in Trail, BC. ART reports to the Vancouver Operational Excellence Group, which in turn reports to the Zinc Business Unit. A simplified organization chart showing the relationship of the AM group to its Teck customers is shown in Figure 2-1. The placement of ART and AM in the Zinc Business Unit is partly historical and partly functional in nature, as the facility is on the Trail Operations zinc smelter site and its technicians are part of the Trail Operations United Steelworkers Union 9705. There was
a short period (2006 – 2009) when ART reported to a newly appointed VP of Technology along with CESL and PTC, Teck’s two other technology laboratory facilities in Vancouver and Mississauga, respectively. When the VP Technology retired in 2009, the role was not filled and ART returned to the umbrella of the Zinc BU. This current reporting line of ART and AM is not ideal, as the facility serves the needs of all business units. To note, the CESL and PTC facilities currently report to the Corporate Office and not a single BU.

![Figure 2-1](image_url)

**Figure 2-1**  Simplified organizational chart showing the reporting line for Applied Mineralogy and the relationship to its Teck customers

The ART Applied Mineralogy group is Corporately funded and provides technical support to all Teck’s mining operations, projects groups and exploration. The ART AM laboratory, and ART as a whole, do not work on a profit-centre or cost-recovery model, as is the current situation for some corporate laboratory testing facilities such as Barrick Technology Centre (Vancouver) and XPS (Sudbury).

A small proportion of AM projects are paid directly by the operations, and these cost-recovery projects are generally derived from Teck operations with a joint-venture relationship, such as Antamina or Red Dog. The proportion of Corporate-pay vs. Customer-pay has changed several times over the past 10 years. The only external customers served by ART AM are those related to Teck in a JV or business relationship, or students working on Teck property projects in Canadian universities, such as the University of British Columbia, University of Alberta or McGill.
The ART AM project budget for 2015 is $1.9M and spans project work for the Zinc, Copper and Coal Business Units, as shown in Table 2-1. Project costs are based on fully loaded, hourly charge-out rates for technicians and scientists (base salary plus benefits), project travel, external testing such as assays, and project supplies. Approximately 50% of the project work under the AM budget comprises true AM testing (ore characterization, process mineralogy and environmental mineralogy). The remainder represents consulting and project management of mining engineering-related projects such as Mine to Mill efforts and collaborative research projects such as CRC-ORE, the cost of employee secondment to Highland Valley Copper, and the laboratory costs for service contracts and support.

Table 2-1  2015 AM Group project budget

<table>
<thead>
<tr>
<th>Customer</th>
<th>Total (000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc Business Unit – Mine Sites (Red Dog, Pend Oreille, Trail)</td>
<td>$365</td>
</tr>
<tr>
<td>Copper Business Unit – Mine Sites (Highland Valley Copper, Carmen de Andacollo, Quebrada Blanca)</td>
<td>$735</td>
</tr>
<tr>
<td>Copper Business Unit - New Mineral Projects (San Nicolas, CESL)</td>
<td>$68</td>
</tr>
<tr>
<td>Coal Business Unit – Mines Sites</td>
<td>$50</td>
</tr>
<tr>
<td>Corporate (CRC-ORE, AM Laboratory)</td>
<td>$709</td>
</tr>
<tr>
<td></td>
<td>$1,928</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Total (000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore Characterization</td>
<td>$151</td>
</tr>
<tr>
<td>Process Mineralogy</td>
<td>$687</td>
</tr>
<tr>
<td>Environmental Mineralogy</td>
<td>$105</td>
</tr>
<tr>
<td>Lab Costs (service contracts)</td>
<td>$323</td>
</tr>
<tr>
<td>Mining Engineering (M2M, CRC)</td>
<td>$549</td>
</tr>
<tr>
<td>Secondment (to HVC)</td>
<td>$113</td>
</tr>
<tr>
<td></td>
<td>$1,928</td>
</tr>
</tbody>
</table>

With the recent expansion of commercial QemSCAN and MLA availability, there has been increased pressure on ART AM from Teck customers to provide comparable cost and turnaround for mineralogical services. The current AM laboratory is not well structured or resourced to compete on a price or turn-around basis, but does work effectively with a full work load. A recent cost comparison of project work completed at ART vs. quotes from commercial laboratories for the same work showed that the ART
AM projects costs were quite similar to those of external labs (Table 2-2). ART AM project costs were actually significantly lower for the plant survey (process mineralogy) testwork, and this is attributed to the long history of this type of testing at ART and familiarity with the ore (Red Dog in this case).

Table 2-2  

<table>
<thead>
<tr>
<th>AM Lab</th>
<th>Plant Survey</th>
<th>Geomet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample #</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>$ per sample</td>
<td>$ total</td>
</tr>
<tr>
<td>ALS</td>
<td>4,123</td>
<td>123,690</td>
</tr>
<tr>
<td>SGS</td>
<td>4,850</td>
<td>145,500</td>
</tr>
<tr>
<td>XPS</td>
<td>6,183</td>
<td>185,490</td>
</tr>
<tr>
<td>ART (actual)</td>
<td>2,161</td>
<td>64,830</td>
</tr>
</tbody>
</table>

2.3. Facility

Key ART AM instrumentation comprises the two Mineral Liberation Analysers (MLAs), one X-ray diffractometer and two research-grade Leica polarized ore microscopes. The instrumentation is supported by sample preparation facilities that are shared with the flotation group, and a dedicated lapidary laboratory for preparation of microscope polished grain mounts. A geometallurgy proxy hardness testing laboratory was established in 2011 as an extension of the geomet mineralogy studies and Teck’s sponsorship of the AMIRA P843 program. A summary of the instrumentation and key equipment in the 2015 ART AM facility are shown in Table 2-3.

Table 2-3  

<table>
<thead>
<tr>
<th>Instruments &amp; Microscope</th>
<th>Laboratory Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 MLA’s Mineral Liberation Analysers with</td>
<td>Sample preparation facility shared with metallurgical laboratory – with various jaw</td>
</tr>
<tr>
<td>Quanta 600 SEM platform &amp; 2 Bruker EDS</td>
<td>crushers, rod mills, sample splitters, pulverizers, Warman cyclosizer, Tyler screens</td>
</tr>
<tr>
<td>detectors. Installed 2003 and 2007,</td>
<td>with Rotap, wet-screening</td>
</tr>
<tr>
<td>respectively.</td>
<td>---------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Instruments &amp; Microscope</strong></td>
<td><strong>Laboratory Equipment</strong></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>2 Leica Ore Microscopes - Research grade (RXPol) fitted with digital cameras. Purchased 2004 and 2006. Cameras updated in 2012 and 2013.</td>
<td>Geomet testing facility Rotary Breakage Tester (RBT), Boyd Crusher (JKCi testing), JK DropWeight (JKDWi), Bond Ball Mill (BWi).</td>
</tr>
<tr>
<td>Clemex image analysis Optical image analysis system with automated stage and inverse-stage reflected light microscope. Purchased 2005 and updated in 2014.</td>
<td></td>
</tr>
</tbody>
</table>

The AM laboratory facility spans 2407 square feet and is spread over two floors in the ART building on the Trail Operations site. Dedicated laboratories are shown in blue outline, shared laboratories are shown in green outline and office space is shown in red outline in Figure 2-2. The shared laboratories comprise the following:

- Pilot Plant where large samples (>10 kg) are split and sized.
- Bucking Room where samples are dried, weighed and split into test fractions.
- Sample sizing laboratories (3).

Facility sharing is quite effective and there have only been minor periods of bottlenecking. During busy periods, the “bucking room” has proven to be one of the main bottleneck areas. The dedicated laboratories comprise the following:

- Lapidary lab. This large laboratory contains many testing areas including the XRD and XRD mounting area, an area where samples are mounted in resin, and an area where the grain-mounts are polished. A small side laboratory is used for sample splitting prior to resin-mounting. The lapidary lab is well equipped for purpose, but could produce much higher levels of output given additional workload, optimal equipment maintenance and staffing.
- MLA lab. This lab consists of two linked rooms. The outer room contains the carbon coaters and some storage of grain mounts. The inner lab contains the two MLAs and their associated UPS units and vacuum pumps. Off-line processing of the MLA raw data sets is performed at individual computers within the offices of the mineralogy technicians.

The instrument laboratories are subject to periodic power and water disruptions being based on the smelter site and within a sixty-year old building. These disruptions have caused minor equipment damage and loss of productivity over the years. For example, the lapidary laboratory was closed down for a few weeks in 2010 for the removal of black mould.

Figure 2-2 ART facility showing location of AM offices and laboratory area.
2.4. Key Equipment

The two FEI Quanta 600 MLAs were installed in 2003 and 2007. Both are currently operational and providing excellent data, however, starting in 2014, the manufacturer FEI no longer supports software upgrades to the 2003 MLA. There are two annual service contracts in place for the MLAs, one for the four Bruker EDS detectors for $21K and for the two MLAs for $45K. In replacement units, it is recommended that field emission gun (FEG) systems be installed, as these allow for higher resolution imaging and much longer filament life. The FEG systems have become the new industry standard.

The Panalytical XRD was installed in 2003. As of June 2015, it has been out of service for two months, and is pending servicing by Panalytical. The instrument experiences a great deal of non-operational time, and seems to be the most impacted by sudden power or water losses, despite the presence of a UPS. In an upgrade or replacement unit, the purchase of an accelerator is recommended. This configuration greatly shortens analysis time and provides higher data resolution.

Other key tools that will require supplementing, maintenance or replacement in the next few years are the two Struers polishing units. The units have had thousands of hours of use per year for the past 12 years and are experiencing higher levels of downtime. A list of key instruments and equipment with their approximate 2015 replacement price is shown in Table 2-4.

Table 2-4 Replacement price for key instruments and equipment in the ART AM Facility.

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Purchased</th>
<th>2015 Replacement Price (est.)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quanta 600 MLA (2)</td>
<td>2003 / 2006</td>
<td>$2,400,000</td>
<td>Operational. Lacking newer applications.</td>
</tr>
<tr>
<td>Panalytical X-Pert XRD</td>
<td>2003</td>
<td>140,000</td>
<td>Currently non-operational pending servicing. Lacking newer applications.</td>
</tr>
<tr>
<td>Carbon Coaters (2)</td>
<td>2006 / 2011</td>
<td>42,100</td>
<td>Good condition.</td>
</tr>
<tr>
<td>Leica-RXPOL</td>
<td>2004</td>
<td>50,000</td>
<td>Currently non-operational pending servicing. Electrical issues.</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>Purchased</td>
<td>2015 Replacement Price (est.)</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------</td>
<td>-------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Leica-RX-auto</td>
<td>2006</td>
<td>40,000</td>
<td>Good condition.</td>
</tr>
<tr>
<td>Leica-DMPOL</td>
<td>2006</td>
<td>25,000</td>
<td>Good condition.</td>
</tr>
<tr>
<td>Leica Stereoscope</td>
<td>2006</td>
<td>12,000</td>
<td>Good condition.</td>
</tr>
<tr>
<td>Struers Polishers (2)</td>
<td>2003</td>
<td>66,000</td>
<td>Operational.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$ 2,775,100</strong></td>
<td></td>
</tr>
</tbody>
</table>

### 2.5. Staffing

In May 2015, the AM staffing consists of 2 full-time mineralogists (PhD – 10 years’ experience and MASc – 10 years’ experience), 1 part-time mineralogist (MSc – 30 years’ experience) and three technicians (3, 5 and 8 years’ AM laboratory experience, respectively). The staffing level in ART applied mineralogy has ranged from a minimum of 3 (one senior mineralogist and two technologists) at the outset in 2003 / 2004 to a maximum of 10 (five mineralogists / mineral processors and five technicians) in 2009, 2011 and 2012. Historical staffing levels are shown in Figure 2-3. The years 2011 through 2013 are deemed to have provided the most optimal blend of staff to meet Teck customer project needs. The inclusion of a mineral processing engineer in the group is considered critical, as it provides a communication link with plant metallurgical staff and the ability to apply mass balancing to mineralogical data sets. It should be noted that the staffing for 2009 through 2013 included a secondee from Teck’s international operations, comprising two geologists and one mineral processing engineer, during the period.
There has been significant AM staff turn-over in the past 10 years. For the technicians, this is attributed, in large part, to their ability to apply for other unionized job openings on the Trail Operations site, and to a lesser extent, fixed term maternity leaves and departures to outside opportunities. This has had a negative impact on the AM laboratory, as specialized training in sample preparation and instrument operation has needed to be repeated with each new employee. The overall impact is that the level of expertise in instrument operation and specialty skills, such as polishing, remain at a relatively basic level. Turn-over amongst mineralogists during the past 10 years has been due to a number of factors, some of which relate to the difficulty in obtaining the right blend of technical and supervisory skills.

2.6. Labour Relations

The Applied Mineralogy group at ART has been the focus of concern for the United Steelworkers 9705 Labour Union since its inception in 2004. The position of the union is that all instrumentation and equipment in the AM laboratory should be maintained and operated by unionized staff solely, in a similar manner to the instruments in the Trail assay laboratory. This has led to several periods of labour relation breakdown, including warnings and grievances against the mineralogists, and associated feelings of tension within the group. Although there have been periods of cooperation and team-work, the instrument-sharing issue remains an ongoing concern.
As of June 2015, mineralogists are barred from setting up any MLA test runs. This situation has reduced the overall technical quality of the MLA analyses to a fairly basic level. This situation is considered a major limiting factor in the smooth and high quality operation of the facility.

The Glencore/Xstrata mineralogy facility in Sudbury, Ontario, is the only other unionized AM laboratory in Canada. It was decided at this facility that only management (mineralogists) would operate the instrumentation. Technicians are restricted to sample preparation. The XPS situation represents the other extreme of labour relations. It unfortunately restricts the development of skilled union employees, but does ensure that instrument operation and data acquisition is performed by the most qualified professionals.

2.7. Workflow and Workload

The AM laboratory facility is very well equipped; however the layout between the two floors in the building is not ideal in terms of optimized work flow. In the current configuration, the mineralogical technicians manually carry samples up and down the stairs several times as part of their normal work flow, as shown by the number sequence in Figure 4. Carrying samples on stairs was noted as a safety concern during the 2015 ART Environmental Health and Safety (EHS) audit, as technicians’ hands are full and they cannot hold stair rails. Optimization of the work process flow should be undertaken. The lapidary lab facility should ideally be located in the lower floor across from the MLA lab, in rooms 135 and 139, thus keeping all sample preparation and testing stages in the lower level of the building, and thereby enhancing the overall work flow.

Quality mineralogical analysis and value-added interpretations are highly dependent on detailed sample preparation activities that include sample selection, crushing / grinding, multiple sub-sampling, weighing, drying, size separations, mounting of samples in resin, polishing and carbon coating. It is not uncommon for these activities to comprise more than 60% of a given project budget. A typical flowsheet for preparation of a metallurgical product, such as a feed, concentrate or tailing, is shown in
Figure 2-4. Sample preparation is the most common bottleneck in the AM group, along with data reporting.

![Workflow diagram for mineralogical study of metallurgical products.](image)

**Figure 2-4**  
Workflow diagram for mineralogical study of metallurgical products.

### 2.8. Productivity

In a strict production sense, the utilization of the ART instruments is quite low, as shown in Figure 2-5 for 2014, with the MLAs begin approximately 50% utilized, and the XRD being only 10% utilized. The facility has several constraints, the most important being irregular work loading. Projects are planned and resourced annually and the test samples are received from mine sites around the world. It is not uncommon for samples to be delayed from weeks to months, and several projects planned to be staggered may arrive together. This irregularity of sample receipt plays havoc with project plans, employee workload and facility utilization. The AM laboratory facility works at its best when near capacity – or as they say in mining – choke fed.
Figure 2-5  2014 AM instrument utilization.
Based on this review, it is believed that the MLA and XRD data output could be doubled given a predictable flow of test samples and the resolution of the various coordination and labour relation issues.

AM test reporting tends to be in a chronic state of backlog. This is attributed to several factors: the need for mineralogists to supervise and review testing, lack of sufficient time allocated in budgets for reporting and to a lesser extent, and the plethora of non-project activities. Data interpretation and reporting require a renewed focus moving forward, as it is the activity where value is given to the operations. The overall ratio of technicians to mineralogists does not seem to be optimal. There is a clear a requirement for more mineralogists who can interact with customers, plan projects, review data sets, turn the data into knowledge and effectively communicate information to sites.

2.9. Outsourcing

2.9.1. Advanced Mineralogy

Applied mineralogy projects often require characterization using advanced instrumentation not available in-house. The ART mineralogists have developed good relationships with service providers at government and university laboratories, specifically in Canada, but also in Australia, that can offer these services. Among the external contractors are:

- CANMET, Ottawa. This facility has been used for electron microprobe analysis of Red Dog Aqqaluk sulphide species, Pend Oreille sulphide species, and SIMS (Secondary Ion Mass Spectrometry) of trace elements in sulphides at Carmen de Andacollo.
- Museum of Natural History / University of Ottawa. This facility has been used to provide electron microprobe analyses for Carmen de Andacollo projects.
- Surface Science Western, London, Ontario. This facility has a wide variety of instruments to measure trace elements in minerals, such as gold in pyrite or arsenopyrite or at mineral surfaces, such as organic flotation reagents.
2.9.2. Automated Mineralogy

The ART AM group occasionally outsources MLA testwork. During a busy period in 2013-2014, Activation Laboratories (ACTLABS) in Ancaster, Ontario completed several batches of automated mineralogy analyses and sent the raw data back to ART for off-line processing. This lab was chosen as it was the only commercial laboratory in North America at the time that offered MLA analysis. Most commercial facilities offer only QemSCAN analyses, and although both systems provide a similar final product, they utilize different software platforms. The AM group wished to receive and review raw data sets using their in-house software licenses. This technical detail should be resolved in future years with advances in application software.

Automated mineralogical work also is completed at external laboratories while completing an integrated parallel program of metallurgical testing for an ART or Corporate project manager. These third party projects typically are put forward by the Corporate projects group for advanced mineral properties that are undergoing pre-feasibility or feasibility testing.

These out-sourcing activities are scrutinized by the unionized workers, who feel it poses a threat to the stability of their jobs, and creates bad feelings in the AM and ART team.

2.10. Project History

The AM group at ART has had lengthy project experience and interactions with Teck’s mining properties and operations. The involvement of ART with mineralogical and metallurgical projects extends back prior to 2004, from work performed at Cominco Research, now known as ART. A history of ART AM projects by commodity or business unit is shown in Figure 2-6. The figure reflects the trend of Teck corporate growth away from zinc-dominant operations to increased diversification into copper and coal. The presence of gold projects in the corporate portfolio is also shown, along with divestment in gold following the 2009 Global Financial Crisis (GFC).
Figure 2-6   ART Mineralogy project history by commodity based on polished sections analysed.

A more detailed history of ART AM projects by site and project is shown in Figure 2-7. The pattern reflects project work in support of new mine acquisitions (Carmen de Andacollo, Duck Pond, full ownership of the Elk Valley coal mines), new property evaluations (Zafranal, Relincho, Mesaba, Nautilus, Teena, White Earth and others), brown-fields development (Aqqaluk, Qanaiyaq, Carmen de Andacollo Hypogene), environmental studies (Antamina) and the gold properties no longer in Teck’s portfolio (Pogo, Williams Operations).

Figure 2-7   ART Mineralogy project history by mine site or project based on number of polished sections analysed.
Based on the preceding description of key features of the Applied Mineralogy Group at ART, a SWOT analysis is presented in Table 2-5 that summarizes key details.

Table 2-5  **SWOT analysis for ART AM facility.**

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Established relationships and project experience with most Teck mine sites.</td>
<td>Current organization structure does not imbed group adequately into Vancouver Projects &amp; Exploration groups.</td>
</tr>
<tr>
<td>Mineralogists have a broad experience base in mineralogical techniques and have studied a range of commodities (Cu, Zn, Au, Ni, PGM other) and materials (rock and process products).</td>
<td>Difficult to quickly scale-up / scale-down staff to meet project needs.</td>
</tr>
<tr>
<td>Technicians are experienced in the preparation of rock and mine samples for optical, MLA and XRD analysis.</td>
<td>Irregular project load.</td>
</tr>
<tr>
<td>Excellent on-site laboratory with sample prep, lapidary prep, 2 MLAs, 1 XRD, polarized light microscopy, image analysis.</td>
<td>On-going labour relations issues and the cumbersome union-centric management structure of ART reduces the effectiveness of group, limits the ability of mineralogists to utilize instrumentation, disrupts work flow and make efficiencies difficult.</td>
</tr>
<tr>
<td>Established relationships with other service providers (commercial labs, university and govt research labs).</td>
<td>Difficult to obtain instrument servicing in remote location (Trail).</td>
</tr>
<tr>
<td>Established member of global mineralogical community.</td>
<td>MLAs are 9 and 12 years old. XRD is 12 years old. Replacement CAPEX is high.</td>
</tr>
<tr>
<td>Established competency in geomet testing (standards &amp; proxy) and its linkage with mineralogy.</td>
<td>No section leader at present.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>The appropriate strategic placement of ART AM would give it more corporate visibility and access to technical project teams.</td>
<td>The current ART focus on water treatment and the project management of large main-site-based projects has reduced the interest in development of AM expertise at ART.</td>
</tr>
<tr>
<td>Increased focus on geometallurgy and environment compliance requires mineralogical inputs and consulting.</td>
<td>The proliferation of commercial mineralogy labs offering MLA/QS and XRD services reduces the desire for a corporate facility.</td>
</tr>
<tr>
<td>A strong technical base in applied mineralogy will be necessary when the industry rebounds. Skills may be lost to the commercial sector.</td>
<td>There is intense price-cutting at commercial labs because of the current industry down-turn reduces desire for project delivery through ART AM.</td>
</tr>
</tbody>
</table>
Chapter 3.

External Analysis - Applied Mineralogy Industry Analysis

In the expensive, technically complex and rapidly evolving field of Applied Mineralogy, it is vital for Teck to understand the following:

- Value that applied mineralogy can provide to a project or operation
- Current and future corporate requirements for applied mineralogy
- Applied mineralogy industry
- Options for service provision

3.1. Value, Loss and Liability

As discussed, applied mineralogy is a diagnostic tool that provides a unique layer of understanding in the analysis of ores, process samples and secondary materials that cannot be obtained using core logging, chemical analyses or metallurgical testing. It describes and quantifies the physical nature of the ores, the types and quantities of minerals present, the grain sizes and intergrowth textures, and in the case of process streams, the liberation characteristics. Mineralogical content sometimes can be inferred from bulk chemistry, but mineral liberation, mineral relationships with gangue minerals, can only be measured using applied mineralogy. The information allows for calculation of theoretical recoveries, theoretical losses, acid-producing characteristics of waste rock and the nature of deleterious elements.

Gu et al. (2014) discuss the economic value of applied mineralogy in the successful installation of ultrafine grinding at Anglo American’s Amandelbult platinum
operation in South Africa. The project capital cost was $250M with annual operating costs of $15M. The installation resulted in reduction of tailings PGM grade by 50%, with an overall 5% increase in PGM recovery. The value created was calculated at US$75M annually, with an NPV of $158M given a 10% discount rate. The metallurgical test work and associated applied mineralogical studies cost $2M, but were critical in assessing the probability and degree of success of the project. The mineralogical data, in this case comprised a detailed understanding of the type and size distribution of PGM losses in the plant tailings, allowed for determination of the degree of increased grinding required to expose or liberate the PGMs, the theoretical magnitude and value of the resulting recovery improvement, and therefore how much should be spent on the installation. The authors report that the mineralogical information brought forward the installation by two years, thus capturing an additional $53M. This is a classic example of the use and value of applied mineralogy in establishing the physical limits of metal recovery at a given grind.

Gu et al. (2014) consider the value of applied mineralogy as being equivalent to the value of information and that this information has the highest value in the high-risk front end of the mining property evaluation curve where uncertainty is greatest. They propose a model that calculates the potential value of mineralogical and metallurgical testing to a project by using a Monte Carlo simulation of the potential returns on investment for a given process change. The standard deviation or spread of the results can be positively impacted by the strategic use of mineralogical information, as shown by the platinum example, above.

The corollary of value gained is loss avoided. Applied mineralogical information is extremely valuable in predicting the presence of negative aspects of an ore to an operation. These may comprise the presence of extremely fine-grained ore textures in a new property under evaluation that will make beneficiation extremely difficult or costly, or the presence of a deleterious mineral that will naturally deport to the flotation concentrate and having a negative impact on sales. In 2000 and 2001, Teck Resources completed a program of bench-scale and pilot-scale metallurgical testing, with detailed applied mineralogical study of both feeds and metallurgical products, as part of the feasibility study of the San Nicolas Cu-Zn volcanogenic massive sulphide property in the
Zacatecas province of Mexico. The fully integrated metallurgical and mineralogical program showed that poor flotation metal recoveries were associated with regions of the deposit characterized by ultra-fine mineral grain sizes. Based on the information from the multimillion dollar 2001 feasibility program, along with other economic considerations, the decision was made not to proceed with project development at that time. The metallurgical program alone would not accurately specify the level of grinding needed for liberation of the copper, zinc and lead minerals or define the spatial location of the problematic textures. The project is under re-evaluation in 2015 with a view to performing advanced geo-domaining using the mineralogical database.

Kahneman and Tversky (1979) were the first to challenge a long-held belief that decision-making in business and other areas is necessarily rational. They developed a behavioural science-based economic concept known as Prospect Theory, which was later revised to Cumulative Prospect Theory (Tversky and Kahneman, 1992). The theory proposes that most decisions are, in fact, made based on a current frame of reference or status quo, rather than future possibilities based on real statistical data. It further purports that there are different risk responses for decisions relating to potential gains vs. potential loss. More weight or concern is given to any risk against possible gains (risk aversion behaviour), while less weight or concern given to risk against possible losses (risk-seeking behaviour). These behaviours can be clearly seen in the mining industry, where any risk against a projected revenue stream is not tolerated (risk aversion), but at the same time there is a willingness to downplay the risk associated with possible recovery upsets related to ore variability or other factors (risk-seeking). These behaviours also can be clearly seen in the increased need for, and acceptance of, process mineralogical testing to ascertain the reasons behind poor processing results (current revenue risk aversion), and the lesser acceptance of ore characterization testing that can predict and reduce the upset of future ore variability (future loss risk seeking), as shown in Figure 3-1.
3.2. Teck’s Mineralogy Requirements

An estimate of annual Teck AM service requirements per operation is shown in Table 3-1. This list is based on the past and current practices of Red Dog, Highland Valley Copper and Carmen de Andacollo, an understanding of the testing that is currently being outsourced, and a projection of necessary testing that currently is not being performed, but could be used to provide value to an operation. The cost per test is based the costs for recent testing performed at ART in 2014.

Table 3-1 Projected annual requirements for applied mineralogy.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Monthly terminal streams</th>
<th>Process optimization</th>
<th>Benchmark surveys</th>
<th>Ore Characterization</th>
<th>Environmental analysis</th>
<th>Petrography</th>
<th>Cost (SCAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Dog</td>
<td>40</td>
<td>12</td>
<td>40</td>
<td>100</td>
<td>10</td>
<td></td>
<td>340,000</td>
</tr>
<tr>
<td>Pend Oreille</td>
<td>36</td>
<td>12</td>
<td>15</td>
<td>100</td>
<td>10</td>
<td></td>
<td>267,500</td>
</tr>
<tr>
<td>Trail Operations</td>
<td>10</td>
<td>40</td>
<td></td>
<td>100</td>
<td>20</td>
<td>20</td>
<td>145,000</td>
</tr>
<tr>
<td>Zn Projects - 1</td>
<td>36</td>
<td>12</td>
<td>40</td>
<td>100</td>
<td>10</td>
<td></td>
<td>175,000</td>
</tr>
<tr>
<td>Highland Valley Copper</td>
<td>36</td>
<td>12</td>
<td>40</td>
<td>100</td>
<td>10</td>
<td></td>
<td>330,000</td>
</tr>
<tr>
<td>Operation</td>
<td>Monthly terminal streams</td>
<td>Process optimization</td>
<td>Benchmark surveys</td>
<td>Ore Characterization</td>
<td>Environmental analysis</td>
<td>Petrography</td>
<td>Cost (SCAN)</td>
</tr>
<tr>
<td>--------------------------</td>
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<td>-------------------</td>
<td>----------------------</td>
<td>------------------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Carmen de Andacollo</td>
<td>36</td>
<td>12</td>
<td>30</td>
<td>100</td>
<td>10</td>
<td></td>
<td>305,000</td>
</tr>
<tr>
<td>Quebrada Blanca</td>
<td>30</td>
<td>100</td>
<td>20</td>
<td>175,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CESL</td>
<td>20</td>
<td>100</td>
<td>20</td>
<td>175,000</td>
<td></td>
<td></td>
<td>50,000</td>
</tr>
<tr>
<td>Cu Projects - 1</td>
<td>30</td>
<td>100</td>
<td>20</td>
<td>175,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu Projects - 2</td>
<td>30</td>
<td>100</td>
<td>20</td>
<td>175,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greenhills</td>
<td>30</td>
<td>20</td>
<td>5</td>
<td>20</td>
<td>100,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fording</td>
<td>30</td>
<td>20</td>
<td>5</td>
<td>20</td>
<td>100,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fort Hills (clays)</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td>20,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exploration</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td>100,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>2,457,500</strong></td>
</tr>
</tbody>
</table>

The list assumes standard analysis types: XRD, SEM-EDS analysis and automated mineralogy, and does not include the requirement for other more advanced techniques. Unit prices for specific tests: Process streams by size fraction ($2500), Ore characterization ($1000), Detailed clay analysis ($1000), Smelter products ($2000), Petrography ($500).

Teck’s base metal operations, Red Dog, Highland Valley Copper and Carmen de Andacollo, actively utilize applied mineralogy in process control, circuit diagnostics and troubleshooting. The mines also employ AM for the characterization of ore in resource drilling that allows for the understanding of ore mineralogy and potential processing characteristics for Life of Mine (LOM) and waste rock for its potential impact on the environment. The recently opened Pend Oreille Mine (POM) has requested similar support.

**Terminal Stream Analysis**

Each of Teck’s Mine sites will benefit from size by size analysis of its terminal streams on a monthly basis, or more frequently when there are new start-ups, as was the case in 2014 for Highland Valley Copper, and is presently the case for Pend Oreille. Terminal stream analysis allows the plant staff to understand plant effectiveness over the past month (or specific period) given the nature of the feed and any plant upsets. It
also allows a tie-in with the site’s geomet model to validate the prediction of concentrator response to the ore block mined over the period. The terminal stream data can be tracked and control-charted between months to review stability in ore mineral liberation in the feed, the type and size of deleterious components in the concentrates and the nature of losses to the tail. Red Dog currently provides its terminal streams per stockpile and this consists of 10 different streams because of the complexity of the circuit and the existence of two final concentrates and two significant plant tailings.

**Benchmarking Surveys**

Full or specific block surveys of flotation concentrators should be completed at least bi-annually to provide a detailed baseline diagnosis of performance. In addition to the information provided by the terminal stream studies, the survey can point to specific banks or equipment that is not performing optimally. The survey is a snapshot in time, and plant conditions must be stable prior to and during the sampling campaign. Best practice in benchmark surveying has been reported by several authors including Lotter (2005). The ART metallurgical and mineralogical group has considerable experience in this type of sampling, analysis and interpretation.

**Process Mineralogy**

Specific campaigns of sampling and analysis are frequently required to diagnose specific circuit issues. These campaigns commonly relate to new installations or circuit reconfigurations, some type of plant irregularity or unforeseen changes in ore characteristics. Timely analysis is required in these cases as they may mean losses of recovery, metal in concentrate and mine revenue. Some mine sites have the ability to do on-site diagnosis. Carmen de Andacollo has an on-site mineralogist who performs optical mineralogical analysis, but where analysis of fine size fractions and trace components is needed, automated mineralogy is requisite. Process mineralogical data was used to support the case for the installation of the IsaMills at Red Dog (McKay et al. 2015, in press). In the case of the Trail Operations smelter complex, diagnostic study of various process products often is required on a rapid turnaround basis in order to keep processes stable and within products within specification.
Ore Characterization

Mineralogical study of specimens from new exploration properties is critical to provide predictive indications of property value. Mining operations are increasingly applying ore characterization to drill core intervals from their resource drilling campaigns. This information is part of a bigger program to build a strong geometallurgical model for the LOM that includes chemical, mineralogical, hardness and recovery information on a spatial basis.

Environmental Mineralogy

This application of mineralogy is quite specialized. It requires background knowledge of the ore body and the mining operation, and then, application of this knowledge to the nature of waste streams that may impact the environment such as dusts, tailings, waste rock and effluents. This is a growing application for Teck as mining properties come under additional scrutiny from local communities, governments and NGO’s. It is also a sensitive subject or confidential subject, as Teck may want to have a preliminary diagnosis of environmental impacts and causes so that the company will be better prepared when they are made public. Environmental analysis often requires creative thinking to determine the correct method to sample and analyze, often trace quantities of micrometer-sized material.

Petrography

This optical study of rocks and minerals in thin section, and supported by SEM study is a key in the understanding rock type and alteration type and extent. It also can explain various textural relationships that cannot be diagnosed in ground ores using automated systems. It is a key tool to explorationists and resource geologists that adds to their logging of cores. Petrography also, unfortunately, is a disappearing form of analysis, with most young mineralogists unable to effectively use polarizing microscopes. In the short term, Teck needs to take advantage of seasoned mineralogists or university researchers to provide this type of analysis. Ideally, the automated systems will be able to move into this field in the near future.
Another important form of petrography is in the study of coal macerals. This is a critical service for Teck Resources as it provides characterization of coal in various seams and, ideally, a prediction of their coking quality. Teck currently uses Pearson Petrographics on Vancouver Island for this service. Research groups in Australia (O’Brien et al., 2007) have made progress in automated optical image analysis of coal, and it is anticipated that this technology will improve rapidly in the near future. ART mineralogy has performed a few interesting MLA studies of coal that show the potential for the use automated mineralogy in benchmarking surveys of coals plants. These MLA studies, however, can only measure coal vs. non-coal particles, and not the specific macerals.

3.3. Porter 5-Forces Industry Analysis

The 5-Forces industry analysis model of Porter (1996) provides a framework to assess the level of competition within a given market. The model reviews all the significant impactors on an industry, including competitors, suppliers, substitutes, buyers (customers), new entrants, regulators and complementors. These forces are then ranked in terms of which ones have strong impacts on a company wishing to enter a given market, and which factors have a weaker impact.

In the case of ART AM, the 5-Forces analysis was used to assess ART’s current ability to compete within the applied mineralogy testing market. This 5-Forces model is shown diagrammatically in Figure 3-2. Shapes shaded in orange represent those forces deemed to have a strong impact on the ART AM testing business, while those shapes shaded in green represent those forces that have a weak to nil impact on the business.
Figure 3-2  Five Forces diagram showing major factors impacting the Applied Mineralogy industry from the perspective of a mining company.


*Industry Competitors*

**Strong Impact:** From the perspective of the ART AM testing laboratory, there are many competitors for Teck’s mineralogy business. These competitors comprise the commercial testing laboratories including SGS, ALS, BV, XPS and FLSmidth, and to a lesser extent, the university and government-funded facilities. Competition between the commercial laboratories for customers is fierce. Each has invested heavily in automated mineralogy and laboratory facilities in multiple continents in the past ten years, just prior to the current prolonged industry down-turn. FLSmidth has invested in automation of the sample preparation facilities that feed the instruments. These commercial labs are actively marketing their instrument capacity and packaging applied mineralogy as a volume-based, commodity-type service. In terms of concentration ratio, SGS, ALS and
BV currently are estimated to hold at least 50% of the industry testing. Price for service is at an all-time low and this is extremely attractive to mining customers, such as Teck, who have constrained budgets. Commercial labs have the additional advantage of providing a full service package that includes applied mineralogy, but also chemical analysis and metallurgical testing, and can provide and manage this service in several continents. As such, samples do not have to be shipped to a single location. From the perspective of Teck Resources (the final customer), these competitors represent partners and service providers (Suppliers, Complementors), as ART AM currently does not have the capacity, in terms of facility or staffing, to handle all of Teck’s applied mineralogy.

Universities and government facilities too, are eager to develop collaborative projects with mining industry partners. This allows them to apply for new grants and continue research efforts. There have been many good relationships developed between ART AM and these knowledge-focused and academic resources that acts to extend the scope of ART AM projects.

From the perspective of the imbedded relationship and experience of the ART mineralogists and mineral processing engineers, there is significantly less commercial competition. This is a very strong positive feature of ART AM that should be exploited and expanded with our current and future Teck clients.

**Buyers**

**Strong Impact:** Applied mineralogy Buyers comprise the Teck corporate customers at mine sites, the corporate projects group, Teck exploration and others who are involved in activities that include bench scale testing, plant operation, product quality analysis, process trouble-shooting, failure analysis or environmental remediation. These Buyers control the selection of AM services.

For Buyers, the three pillars of Quality, Price and Turnaround are the key factors in service selection. The AM group prides itself in providing quality analysis and data interpretations to Teck. At present, however, there is a real concern of skills loss moving forward as the group staffing is down-sized. With respect to Price, Buyers are always
cost-sensitive, and the current industry down-turn has made this even more acute, meaning that test programs are deferred or cancelled, or vendor selection is made based, to a certain extent, on price. At present, ART AM is quite an attractive option as the majority of testing is funded by the Corporate office, thus providing essentially free services to Teck Buyers. With respect to Turnaround, ART AM cannot compete with the capacity available from commercial vendors, and especially so as the ART AM capacity is being reduced.

**New Entrants**

**Strong Impact:** There is a high cost of entry into the applied mineralogy testing business. The cost of setting up a facility, purchasing instruments and staffing it with skilled people is complex and expensive. In this business case analysis, the cost of ART AM to continue to compete in the AM market by upgrading their instruments, restructuring and re-training their group is considered a form of New Entry, and this cost is high.

**Weak Impact:** The only possible new entrant in the context of ART AM might be the development of an AM laboratory in another of Teck’s corporate facilities, such as at CESL in Richmond. This scenario would have a similar 5-Forces scenario as for ART, and not be advisable based on the industry downturn and commercial service availability. But in terms of a SWOT analysis, the CESL site has a more central, better serviced, more attractive business location that ART and a non-unionized work force, but it does not have the technical history of the ART staff. This potential lab would be starting near square one.

**Suppliers**

**Strong Impact:** Corporate Sponsor: The most important supplier to ART AM is Teck itself. The annual budget for ART is provided by the Teck Corporate office and the breakdown of ART project work is structured based on priority to the company. The recent company focus on water treatment projects in support of the Elk Valley coal mines has removed the focus from applied mineralogy projects and reallocated capital and human resources to more pressing projects. In addition, the industry down-turn has
meant that budgets have been reduced. As a Supplier, Teck Corporate must approve the capital expenditure for AM instrument upgrades for the group moving forward.

**Weak Impact:** Instrument Suppliers: The ART AM facility has several key instrument and equipment suppliers, and a wide variety of lesser ones. The main suppliers are the manufacturers and distributors of the MLA and XRD instruments. These are a relatively neutral force, but there are latent concerns with the ever increasing price of service contracts and poor performance on service requests. FEI, the manufacturer and developer of both MLAs and QemSCANs, an industry monopoly, has recently dropped its Minerals division, as sales have been poor. This impacts the future development and service of the ART MLAs and also the QemSCANs of competitors. On the positive side, there are two new entrants into the automated mineralogy market, Zeiss and Tescan. Panalytical, formerly Philips, the manufacturer of the ART XRD is a fairly responsive, long-term supplier, and is not of immediate concern. Other key suppliers include Buehler and Struers for lapidary equipment and supplies and Leica for microscopes. The various university and government laboratories that provide more sophisticated mineralogical analyses to support in-house projects can be considered a Supplier to ART AM, but are considered here more as a Complementors, and are dealt with in that section.

**Substitutes**

**Weak Impact:** Although there is no real substitute for applied mineralogy in the greater sense, there a real possibility that a new technology may be developed that provides an improved result (a benefit to Teck) but renders redundant the current technology and capital investment (a risk to ART AM). An example of a disruptive technology was the replacement of classic, manual polarizing microscope analysis with computerized automated mineralogy in the 2000s. Substitutes available in the 5 to 10 year window may include Computerized Tomography (CT) or Hyperspectral Imaging. They will impact ART AM in the next 5 years by the requirements for technology trials and validation against standard, more accepted, mineralogical techniques.
**Complementors**

**Weak Impact:** Future growth of Teck Resources by the acquisition of new mines and advanced mineral properties will increase the need for skilled applied mineralogical knowledge, testing and interpretation.

There has been increased industry uptake of the use of automated mineralogy for plant surveys and geomet programs in the past decade. This has partly been the result of industry, including Teck, sponsorship and participation in collaborative research programs such as AMIRA P9 (metallurgical modelling) and P843 (geometallurgy).

Government and university laboratories that provide advanced mineralogical services are considered as significant complementors, as they are an important value-added service and support to ART AM projects for Teck.

**Regulators**

**Weak Impact:** Mineralogical data increasingly is used in documents subject to public disclosure of information, such as new property valuations or environmental reviews (Bye, 2011). As a result, there is a strong possibility that within 10 years, AM laboratories will require accreditation, similar to analytical laboratories. This will necessitate the use of accredited commercial mineralogical laboratories rather than in-house laboratories, so that there is no perceived conflict of interest. This may negatively impact ART, as this form of testwork may need to be performed at an external facility. It is important to Teck and ART AM to differentiate between testwork used for possible disclosure, such as property divestment, and resource development, and that allocated for exploration, process optimization or geomet modelling.

**Summary**

This Porter’s 5-Forces analysis clearly demonstrates the most significant industry forces that impact the 2015 ART AM business. These comprise:

- the large availability and technical capacity of commercial competitors in applied mineralogy,
• the ability of ART's Teck customers to select service providers based on quality, cost and turnaround,
• the high cost of entry for ART AM to upgrade and streamline their current facility,
• the continued support of Teck Corporate to supply OPEX and CAPEX for the AM facility.

3.4. Tests for a Core Resource

Value

In terms of value, applied mineralogy is a unique diagnostic capability, unlike chemical analysis which measure elements, or metallurgical testing which measures the recovery or loss of elements. The value proposition for a mining company to use AM is its ability to identify opportunities for asset enhancement, such as improved plant recoveries based on diagnosis of mineral deportments in the circuit, and its ability to mitigate risk, such as the diagnosis of the deleterious minerals within a waste rock pile as part of an effort to minimize acid mine drainage. ART AM, as part of Teck, holds to these values and is focused on the informed development of mineralogical testing programs, acquisition of quality data sets and knowledgeable interpretation of the data in the context of the specific problem. There sometimes can be a long timeline (months, years) between testing and ultimate value realization.

Rareness

In terms of rareness, automated AM and XRD testing services are not rare. They were rare ten years ago when automated mineralogy was not available commercially, but not at the current time.

Imimitability

The specific testing operations at ART AM can be copied readily by a competitor, however AM's specific experience with Teck's ores and relationships with Teck customers has taken many years to build, and is hard to duplicate in short order. Also,
the position of ART AM within Teck allows a level of confidentiality to projects than is advantageous.

**Leverage**

ART AM has the unique ability to participate in technical discussions for many of Teck’s mines and projects, allowing it to assess when AM testing would be appropriate and could add value. Also, the learnings from one Teck project can be applied to another project without providing any conflicts of interest, thus developing an important corporate competency and memory.

### 3.5. PESTLE Analysis

A PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis of the applied mineralogy business is shown in Table 3-2. On the economic front, the single most immediate feature that impacts Teck, ART and AM in 2015 is the current severe economic down-turn in the mining industry. This means that there are very few funds available for ore testing or new process development. Unfortunately, there is no shortage of process problems, process monitoring or ore deposit modelling to perform, but operating site budgets have been severely reduced and funds are being spent only on critical, immediate problems that have a 6 month to 1 year pay-back window. At the same time, the ART budget has been reduced and staffing levels reduced by two persons (~4%) overall. In the past six months, one technician position was eliminated in the applied mineralogy team and a second technician temporarily reallocated to another group. This hampers the ability for the group to meet time-dependent project commitments.

Looking forward, there are some common themes. Mining will become an increasing costly and risky endeavor as lower grade ores or ores in harsh environments are exploited. This will require significant due diligence on the part of mining companies to ensure financial institutions that they are a good investment. Some of this due diligence work will be focused on applied mineralogy. At the same time, there is increased social pressure from governments, communities and NGOs for responsible
and sustainable mining. This means providing jobs on one hand, and minimizing negative impact to the environment on the other. Baseline studies and on-going monitoring of the environment and communities will increase, as well as the need for public disclosure. Effective mineralogical testing and reporting is an important part of this process, particularly for documentation of the presence or paucity of any potential deleterious components.

Technology will continue to advance. In the short term, the current MLA/QemSCAN FEI instrument monopoly will end as the second tier of instruments attract increased industry sponsorship. Sample preparation and instrumental analysis will become more and more automated, driving the need for new competencies amongst mineralogists. Data will proliferate pushing the increased need for meaningful analysis and modelling in spatial or process terms, along with effective communication and partnership with operations. New instruments currently in the developmental stage will become commercially available. Sensors and scanners will allow applied mineralogy to become a process control tool. The distinction between lab and field or plant will blur for many applications. There will be increased industry collaboration with universities and government facilities to utilize advanced technologies.

Table 3-2  PESTLE Analysis of Applied Mineralogy at ART

<table>
<thead>
<tr>
<th>Factor</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Political government policies, political change, intervention, taxes, etc.</td>
<td>Governments will continue to support mining as it provides employment and a strong tax base, but there will be political pressure derived from social (community and health) and environmental fronts for increasingly responsible mining, base-line studies, due diligence and disclosure (discussed below).</td>
</tr>
<tr>
<td>Economic economic growth, exchange rates, inflation rate, etc.</td>
<td>The mining industry is in a prolonged down-cycle. There is little extra capital available for mining companies to spend on anything than critical project and research efforts. New mines will continue to develop lower and lower grade ores. This brings on an increased need to reduce risk by better understanding the ore body and its processing characteristics. Banks will want assurance on new ore deposit development. This will increase the need for thorough due diligence studies of the ore body. Mines will be developed in harsh environments such as undersea and space, also bringing also the need for assurance. Increasing energy costs for ultra-fine grinding of low-grade ores will require new processes to be developed that will require process mineralogical</td>
</tr>
</tbody>
</table>
### Factor | Detail
--- | ---
**study.**  
The high price of newer technologies will drive increased university / business collaboration.

**Social Cultural aspects (i.e. health, demographics, career attitudes, etc.)** | There will be growing public pressure for responsible mining.  
Mines will need to step up activities to provide assurance to the public of the composition of any discharges (water, air, dust, tailings, other).  
There will be an increased need for base line studies and monitoring of mining activities as communities demand to know the impact of mining on their region.  
There may be a skills loss in the field of applied mineralogy as the Baby Boomers head to retirement. This will transition into a generation of mineralogists focused on modelling, rather than acquiring data.

**Technological R&D, automation, rate of technological change, etc.** | In the short term, the next generation of automated mineralogical systems (TIMA, Zeiss) will have put pressure on the current monopoly of MLA / QS systems.  
Technological advancements and competition may bring down the price and speed up the acquisition of automated mineralogical information.  
Technologies currently in the experimental or validation stages, such as computerized tomography (CT) will become commercially available.  
Tools will become more compact, more available and cheaper.  
More sensor-type tools will be in use at the mine site to collect data.  
Mineralogical data will be automated and become a process control tool.  
Data will proliferate and there will be an increased requirement for skills to meaningfully interpret the data and model it into process systems and deposit models.

**Legal legal issues and changes to laws** | Increased regulatory need for mineralogical support in due diligence studies (PFS & environmental studies).  
Environmental and other litigations will require forensic testing.  
Mineralogical laboratories will require accreditation.

**Environmental ecological and environmental aspects** | Increased need for mineralogical due diligence in environmental studies (e.g., dusts, waste rock, tailings, soil contaminants)  
Environmental base-line and on-going studies will be required that include applied mineralogy.

### 3.6. Mineralogy Service Options

#### 3.6.1. Automated Mineralogy

Automated mineralogy (MLA, QemSCAN and TIMA) analyses can be obtained through commercial laboratories in most continents (Table 3-3). Significant capacity is
available through the major commercial laboratory chains: SGS, ALS, BV and ACTLABS, but significant expertise in automated mineralogy also is available through specialized mining service providers such as FLSmidth (Salt Lake City, Utah), Hazen Research (Golden, Colorado) and MINTEK (Johannesburg). Automated mineralogy can be obtained through active corporate technology facilities with extra capacity who work on a cost-recovery and/or profit centre basis. In Canada, these providers include the Barrick Technology Centre (Vancouver) and the Glencore XPS facility (Sudbury).

### Table 3-3  List of significant commercial facilities offering automated mineralogy services.

<table>
<thead>
<tr>
<th>Company</th>
<th>City</th>
<th>Country</th>
<th>Automated Mineralogy</th>
<th>XRD</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canada / US</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ActLabs</td>
<td>Ancaster</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ALS (G&amp;T)</td>
<td>Kamloops</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BV - ACME</td>
<td>Richmond</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SGS (Lakefield)</td>
<td>Lakefield</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRC</td>
<td>Saskatoon</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>XPS</td>
<td>Sudbury</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>FLSmidth</td>
<td>Midvale</td>
<td>USA</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hazen Research</td>
<td>Golden</td>
<td>USA</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>International</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALS Global</td>
<td>Brisbane</td>
<td>Australia</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BV - AMDEL</td>
<td>Adelaide</td>
<td>Australia</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SGS</td>
<td>Perth</td>
<td>Australia</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SGS</td>
<td>Santiago</td>
<td>Chile</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ALS Global</td>
<td>JoBurg</td>
<td>South Africa</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SGS</td>
<td>JoBurg</td>
<td>South Africa</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MINTEK</td>
<td>JoBurg</td>
<td>South Africa</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Numerous universities now own automated mineralogy instruments (Table 3-4). In Canada, these include the University of Alberta in Edmonton, Queen’s University in Kingston, Ontario, the University of Manitoba in Winnipeg and Memorial University in St. John’s Newfoundland. The university instruments are used for student projects and in
support of collaborative research projects with industry, but can available on a limited basis to keep instruments busy and graduate students employed.

This breadth of service has only come of age in the past ten years, and subsequent to the installation of the ART AM facility, except for the XPS facility which evolved out of the original Falconbridge Technology Centre.

Table 3-4  List of Canadian universities with automated mineralogy capacity.

<table>
<thead>
<tr>
<th>Company</th>
<th>City</th>
<th>Country</th>
<th>Automated Mineralogy</th>
<th>XRD</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memorial University of Newfoundland</td>
<td>St. John's</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>University of Alberta</td>
<td>Edmonton</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>University of Manitoba</td>
<td>Winnipeg</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Queen's University</td>
<td>Kingston</td>
<td>Canada</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

3.6.2.  X-ray Diffraction Analysis

As noted above, all commercial laboratories that provide services to the mining industry provide X-ray diffraction analyses with Rietveld refinement. XRD is a very useful tool to quickly determine the crystalline components of a sample and greatly complements the automated mineralogy work. It should be noted that clay mineralogy studies by XRD are a very specialized form of analysis and only should be undertaken at laboratories with appropriate experience.

3.6.3.  Electron Microprobe Analysis

Electron microprobe analysis is a key complementary technique for automated mineralogical studies. As an example, MLA or QemSCAN analysis of a pyrite grain uses energy dispersive spectral analysis (EDS) to measure the content of iron (Fe) and sulphur (S) with a lower detection limit of approx. 0.3 to 0.5 wt.% by element. If arsenic, for example, occurs within the crystal structure of the pyrite at levels less than 0.3% wt.% (3000 ppm), it will not be detected by EDS. Electron microprobe analysis uses a different technique – wavelength dispersive spectrometry (WDS) to measure the
elemental composition of minerals. The detection limit of WDS analysis is much lower than for EDS analysis and can detect the arsenic to a level of approximately 0.02 wt.% (200 ppm) in pyrite. For applied mineralogical studies, this can be a key piece of information and is used in the construction and optimization of the MLA/ QemSCAN mineral database library.

Electron microprobe analyses are available through commercial facilities (Table 3-3), universities (Table 3-4) and government laboratories (Table 3-5).

**Table 3-5** List of Canadian government research facilities offering electron microprobe analysis.

<table>
<thead>
<tr>
<th>Company</th>
<th>City</th>
<th>Country</th>
<th>Automated Mineralogy</th>
<th>XRD</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANMET</td>
<td>Ottawa</td>
<td>Canada</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Museum of Nature</td>
<td>Ottawa</td>
<td>Canada</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ontario Geological Survey</td>
<td>Sudbury</td>
<td>Canada</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

3.6.4. **Advanced Techniques**

There are numerous advanced mineralogical techniques useful to the mining industry that can be accessed through university and government facilities. This paper will not attempt to describe the usages for each of these techniques, but they are used to provide even lower levels of elemental detection and elemental / molecular information of very thin surface layers on minerals. A non-exhaustive list of these facilities is provided in Appendix 1.

3.6.5. **Classical Mineralogy**

Classical petrography and ore microscopy analysis are a relatively rare and specialized service typically performed by university staff and / or experienced mineralogists and geologists, some retired. These optical microscopy techniques are rapidly fading out in the digital age, but still provide a value. Petrography, with the support of SEM analysis, remains the main tool for identifying rock type (lithotype) and
the associated types and levels of mineral alteration. It is a fairly rapid process for a skilled petrographer to work through numerous thin sections from the same ore body qualitatively to characterize key variations in ore emplacement and alteration. Similarly, ore microscopy is a valuable aid to programs of automated mineralogy. It rapidly can identify the mineral assemblage and any associated special features that may cause complications in automated study. In some cases, the viewing of a single polished section by a skilled microscopist can identify or solve a processing concern without the need for detailed sizing and SEM study. Such classic analyses, however, are not designed for collection of large sets of statistical data (point counts, liberation counts, etc.), and therefore are not practical in determining subtle differences in liberation or modal mineralogy by size fraction.

To obtain these services, it is best to obtain a reference for a skilled classical mineralogist. It is hoped that the current optical image analysis systems, which are very complex and typically user unfriendly, will continue to be improved and allow the use of digitally captured optical information for mineral studies, and revitalize the application of petrography and ore microscopy.

3.7. New Technologies

3.7.1. Sample Preparation

Preparation of test samples for analysis by automated mineralogical techniques is extremely labour intensive and is the biggest single contributor to the total time needed to complete an analysis and the ultimate cost of the analysis. The detailed work flow used at ART was shown in Figure 2-4 and clearly demonstrates the labour-intensive nature of the mineralogical preparations. Several recent innovations or applications of previously existing technology to applied mineralogy are joining the mainstream, and are discussed below.

Robotic Sample Preparation

The new FLSmidth Ore Characterization and Process Mineralogy facility in Salt Lake City, Utah has developed and installed complete robotic sample preparation
facilities that can crush, grind and split test samples ahead of automated resin mounting and automated grinding / polishing (FLSmidth, 2014 and Appendix A). The innovators at FLSmidth, led by Wolfgang Baum, an experienced mineralogist formerly with Phelps Dodge and PMET, recognized an opportunity to take advantage of the data capacity potential of the automated mineralogy instrumentation. As such, a fundamental change was needed in sample preparation logistics. FLSmidth, as part of its wide range of services to the mining industry, will also design high volume robotic sample preparation and mineralogy laboratories for customers such as Teck. These FLSmidth robotic facilities are now in use at the corporate Freeport McMoran applied mineralogy laboratory in Tucson, Arizona.

**Polishing and Grinding**

Significant technological advancements have been made in the field of sample preparation in the past 10 years. In the 2000s, both Buehler and Struers developed fully automated grinding and polishing systems in the Vanguard 2000 and Hexamatic instruments, respectively (Appendix A). These systems are user-loaded with a range of platens, cloths and grits, are programmable by the user for specific polishing regimes, and are able to take up to 6 resin-mounted samples through multiple stages of fine-grinding and polishing.

There has only been only sporadic take-up of these systems in applied mineralogy laboratories, largely because of price. Commercial operators have preferred to invest money in the SEM instrumentation and rely on hourly labour to perform the sample preparation. The Vanguard system is currently in operation at CANMET laboratory in Ottawa, while a precursor to the Hexamatic system is in operation at the Anglo Research laboratory in Johannesburg. Anecdotally, the constancy and quality of polish achieved for similar ore suites is far superior to manual polishing. With the general loss of skills and decline in interest in the area of manual polishing and metallography, and the advanced robotic systems for sample preparation ahead of polishing, the automated systems will become a more important feature of laboratories in the future.
Automated Instrument Loading

In addition to robotic sample preparation, the FLSmidth facility in Salt Lake City has worked with automated mineralogy supplier Tescan to develop an automated instrument loading system. At present, MLAs and QemSCANs are batch loaded with up to 17 polished grain mounts for analysis. The instrument is optimized manually and analysis parameters set using the computer interface. Analysis of the sample batch can take between 8 and 48 hours depending on the requirements. There is significant instrument down-time associated with run shutdown and the re-loading process. The new auto-loading TIMA (Appendix B) can load up to 100 samples for analysis, reducing overall manpower requirements and down-time.

3.7.2. Instrumentation

Tescan TIMA and Zeiss Mineralogic

The main automated mineralogy systems on the market are the MLA and QemSCAN, both presently owned by FEI after acquisition of the IP from Australian government laboratories. The recent economic downturn has turned FEI’s business interest away from the mining sector to more profitable areas dominated by TEM’s, such as health sciences and microprocessors. As a result, the continued development of the MLA and QemSCAN systems has lagged and mining customers have become impatient with service. Also, many of the original systems have reached the 10 year age bracket and are due for replacement. Two new vendors have recently appeared, specifically Tescan and Zeiss, both well known for SEM imaging systems (Appendix B). The Tescan TIMA is gaining industry uptake and is installed at several mineralogical facilities. Anecdotal information indicates that the mineralogical application software is less developed than QemSCAN and MLA, but the vendors are very responsive to industry input, and its development is imminent.

Zeiss Xradia 520 X-ray Microscope

Computer assisted tomography (CAT) has been in use in the health sciences field for over two decades. Improved computing power and miniaturization have allowed for Zeiss and Bruker to develop CAT systems for the mining industry (Appendix C).
Mineralogy studies using CAT are still at the research stage (Evans et al. 2015), but are quickly developing momentum. The service is not offered commercially, but can be obtained through various facilities such as JKTech (Brisbane), University of Utah (Salt Lake City) and Mintek (Johannesburg) on a research test program basis.

CAT allows minerals to viewed in 3 dimensions, removing the stereological (2D slicing) bias present in all grain mounts analysed by MLA or QemSCAN. A significant feature of the CAT process is that samples do not require the same labour intensive resin-mounting and polishing of the MLA and QemSCAN. Test samples, such as metallurgical product size fractions, can be loaded directly into thin capillary tubes and then placed into the instrument. The size of particles for detection is based on the defined volume for scanning, but is capable of imaging to less than 5 micrometers. The system can readily locate gold grains against a background of quartz based on their X-ray response, but has more difficulty distinguishing between sulphide minerals in a massive sulphide sample. To date, there is no ability to obtain an elemental signature for a phase, MLA/QemSCAN support is needed to define the species present. Another consideration is that the system produces extremely large data files, with storage requirements an order of magnitude higher that needed currently for an MLA.

3.7.3. CoreSCAN / HyLogger

Rack-mounted sensor systems for spectral mapping of drill core have been developed by various vendors in the past few years. In 2014, SGS developed a professional relationship with Corescan to market their sensor technology (Corescan 2014, Appendix C). Corescan has a technical group in their Australian head-office that work with customers to interpret the datasets. CSIRO out of Australia developed a competing system, the HyLogger, which is now being marketed through BV (ACME in Canada). These sensor systems are aimed at meeting the needs of rapid data acquisition and analysis of mineralogy for drill core that would support the standard visual core logging. They are highly applicable for ores with phyllosilicate alteration assemblages, such as porphyry copper systems.
Chapter 4. ART AM 5-Year Business Strategy

Chapters 1 through 3 have provided a definition of applied mineralogy and its key applications in the mining industry, a detailed description of the current structure and technical capabilities of the ART AM facility and team, and a business case analysis for applied mineralogy from the perspective of Teck Resources. This section will discuss potential scenarios for ART AM business strategy moving forward.

4.1. Scenarios

4.1.1. Scenario 1 – Out-source Mineralogical Testing

Historically, large corporations such as Falconbridge, Sherritt, Inco, Noranda, Newmont, Amax and others, were vertically integrated, with all services performed under the company umbrella. This provided a level of self-sufficiency when service providers were not available and led to development of much corporate capacity and intellectual property. Teck’s 100 year old Trail Operations smelter site is an excellent example of this business model. In the early decades, the company employed glassblowers, seamstresses, cooks, farmers and many other services, as the company existed within an isolated valley and the company had to have guaranteed access to these services for its survival. Moving forward, these services are now out-sourced and there are numerous vendor and contract service options. The Trail region is rife with small contractors that provide various trades and labour to Trail Operations.

Outsourcing theory states that companies favour outsourcing of their non-core competencies, thereby avoiding spending capital which could be better utilized on other corporate needs, and transferring capital costs to variable costs that can be better planned and managed (Steenkamp and van der Lingen, 2014). The authors also suggest that the mining industry in particular also uses out-sourcing to mitigate the
problem of acquisition and retention of skilled people. Demographic and industry / economic cycles have impacted severely the mining industry’s access to skilled engineering and geological professionals, and have been a major factor in the push to develop more robust automated systems.

Steenkamp and van der Lingen (2014) provide a strategic framework for decision-making in the outsourcing process. Their five pillars comprise operational cost, capital efficiency, flexibility, relationship and competency (Figure 4-1). Operational cost, capital efficiency, flexibility and competency factors all favour a model of outsourcing of Teck’s applied mineralogy needs. Project relationship needs, however, are better handled within the organization. The ART AM mineralologists have developed strong ties to the Teck mine sites, corporate projects and exploration groups, and are in a strong position to provide value-added interpretation of mineralogical data.

![Figure 4-1  Key factors to consider for a decision to outsource.](image)

After Steenkamp and van der Lingen (2014).

The ART AM group produces two significant outputs: 1) data and 2) informed mineralogical interpretation and project support to Teck’s operations and projects. When discussing out-sourcing, it is important to keep this distinction. The testing functions in the ART AM laboratory are sample preparation and instrumental sample analysis using the two MLAs or the XRD. As noted, there are numerous laboratories in Canada and globally that readily can perform these services. Data interpretation and consulting, however, are not captured as readily in a commercial laboratory, as they key strategic
competencies of a company, as captured under the Relationship and Competency factors.

A spider plot showing a relative gap analysis between AM testing, AM technical consulting and commercial testing for the five key considerations of Steenkamp and van der Lingen (2014) is shown in Figure 4-2.

![Spider plot showing relative position ART AM and commercial testing for five key outsourcing considerations.](chart)

Figure 4-2  Spider plot showing relative position ART AM and commercial testing for five key outsourcing considerations.

A significant benefit to out-sourcing of mineralogical testing is the ability to rapidly scale-up project requirements and fast-track testing without the concerns of staff availability in-house. SGS presently uses a form of equalization of test loading amongst its various applied mineralogy sites. Each of their sites utilizes the same instrument (QemSCAN), thus work for a particularly large project can be balanced between the Vancouver and Lakefield lab sites. A similar advantage to Teck customers is the ability to downsize testing requirements without impacting Teck’s staffing load, although short-notice cancellation of large projects may incur charges.
A second spider plot showing a gap analysis of ART AM vs commercial laboratory testing for the key pillars of price, quality and turn-around is presented in Figure 4-3. Commercial laboratories are clearly ahead in terms of volume / capacity and turn-around.

![Spider plot showing relative position of strengths and weaknesses for ART AM vs. Commercial Laboratory.](image)

**Figure 4-3**  Spider plot showing relative position of strengths and weaknesses for ART AM vs. Commercial Laboratory.

Another benefit to out-sourcing is that it can leverage the experience / skills of the specific providers, and has a broader geographic coverage. The geographical breadth of commercial laboratories will save money in sample transportation and retail mining testing within the region.

A key aspect to out-sourcing is that appropriate controls must be put in place to manage the process. This includes the preparation of contracts that clearly list deliverables and quality expectations. Most of the commercial laboratories are eager to booking specific blocks of dedicated instrument time for specific customers. This
services their needs in keeping instruments utilized, and serves Teck’s needs by guaranteeing instrument time.

It is imperative that project goals and sufficient background information are communicated to the service providers, and that appropriate samples are selected, and the sample preparation and analysis selection is optimized to meet the objectives. Testing must be strictly monitored to ensure it meets project needs and meets quality requirements. A quality control program should be instituted that includes blank duplicates and repeated analysis of control sample sets that span a variety of parameters (size fraction, mineralogy). A Teck representative should work with the commercial mineralogist to produce the optimal mineral reference library, test conditions and data output format. All mineralogical test data must be archived in a central repository within the company, as it represents a key data base for future interrogation. The test data outputs will be validated by Teck mineralogists, and the final data synthesized and reported to Teck customers.

An out-sourcing scenario will have a significant impact on the ART AM laboratory and staff. There would no longer be the same requirement for sample preparation and instrumental analysis, and the group may require no technicians moving forward. In Section 2.6, this study briefly discussed the on-going labour relations problems within ART and AM, which is lowers the overall level of technical quality and responsiveness of the facility, and the ability of ART to attract and retain key technical staff. A decision to out-source mineralogical testing would resolve this labour relations problem for AM, but unfortunately, would exacerbate ART labour relations moving forward.

In an out-sourcing scenario, mineralogists would be required for project management, monitoring of out-sourcing and customer communications. The instruments will no longer be required, and could perhaps be given to one of Teck’s operations for use. Highland Valley Copper would be a good recipient for the XRD instrument, given its ongoing clay mineral concerns. MLAs are more problematic to place as they require adequate, well trained staffing to prepare and run samples, and as the instruments are 10 years old, they are more prone to break-down. The mining and
metallurgy group at University of British Columbia, which has received sponsorship from Teck, could be a good recipient for an MLA.

4.1.2. Scenario 2 - Update and Expand the present ART AM facility to meet all of Teck’s requirements

This scenario plans for the expansion and upgrading of the current ART facility so that it can perform all of Teck’s mineralogical testing. This represents a significant step change of service level and expectations from the current facility, and is defined here as the new Teck Mining Mineralogy Facility. The projected applied mineralogy needs for Teck Resources were shown in Table 3-1. These estimates are conservative and so fairly realistic for the next 5 year period, and represent a 2 to 3x increase in the current quantity of testing and reporting. These requirements would be expected to increase as the mining industry recovers later in the decade.

Significant business planning will be required to build the Teck Mining Mineralogy Facility. Based on the corporate requirements noted above, the facility size, lay-out, work flow, instruments, project and sample tracking and staffing requirements must be assessed:

- Additional workspace will be required for the upgraded service level. A doubling of the current 2400 sq ft. to 4800 sq ft. is estimated, although there is some optimization of the current facility that could be achieved. This area is available within the ART facility, but will sacrifice other labs and offices.

- A complete re-alignment of the current work-flow is required, as noted in Section 2.7, to optimize sample preparation and analysis.

- A LIMS system of chain of custody, sample receipt, log-in and sample tracking will be needed and must replace the current simple Excel-based system.
• The laboratory will require accreditation, as the projects deriving from the Project Group would be used in Prefeasibility and Feasibility studies. Some applied mineralogy SOPs are already in place and can be expanded.

• Standardized reporting protocols and responsibilities must be developed.

• The current instruments will require replacement and upgrading, requiring a large capital expenditure. The need for a third MLA instrument is anticipated. The current tungsten MLA systems should be upgraded to FEG systems. The choice of instrument type (QemSCAN, MLA, TIMA or Mineralogic) needs to be re-evaluated. The new XRD system should be a high energy system for increased detection and faster analysis time. Combined, these instruments will cost in region of CAN$4M.

• Automation should be considered for sample preparation and polishing to ensure consistency and quality, and to better deal with staffing fluctuations amongst technicians.

• Overall staffing must be increased. As per a 2.5x increase in workload, this would require 8 to 10 technicians, and to provide the same level of laboratory supervision, data QA/QC, technical data interpretation and client communication, 8 to 10 professionals including mineralogists of different levels, technical project managers and metallurgists.

• Staff technical training and development activities must be updated and annualized.

There are numerous concerns with this scenario:

• The current ART facility is in a very old building on the Trail Operations site. It suffers from numerous Trail Operations site-based challenges including power and water outages, and asbestos and black mould. Renovations are very expensive and difficult to organize.
There are the ever-present labour relations issues associated with performing effective mineralogical testing which severely reduces the effectiveness of the facility.

In order for this Teck Mining Mineralogy Facility scenario to be successful, the facility ideally should be moved to a new site. The facility should be:

- In a newer structure with modern services where work flow, instrument position and office space can be optimized, and there is improved access to services.
- Staffed by non-union employees to allow for more effective employee recognition and reward for contributions, and control of the hiring process.
- Located on transportation routes (truck and air) so that samples can be quickly received from various international locations and the instruments can be readily accessed by service agents.
- In an attractive region to attract talented scientists (e.g. Vancouver, Santiago) to staff the facility.
- More effectively positioned within Teck Resources so that it participates with business unit teams on projects that require AM testing. This imbedding will allow for the optimal AM project definition and value delivery, as well as for tight scheduling of instrument time for specific projects.

This scenario will have a major impact on the present ART AM facility. It will cease to exist, as the new high-tech, smoothly functioning laboratory is built. Employees currently working in the AM group would need to decide if they want to make the move to a new facility and potentially (for union) employees, under a different contract.
4.1.3. **Scenario 3 – Update of Current Facility**

Scenarios 1 and 2 have discussed the requirements, strengths and weaknesses of a) outsourcing and b) expansion, and their strong impact on the current facility. Scenario 3 presents a blend of scenarios that retains aspects of the current mineralogy testing services of ART, but at a more limited level, and also explores taking responsibility for effective out-sourcing service options and making the best use of mineralogy expertise within Teck.

Under this model, the corporate AM facility would have a small, upgraded instrument base that would be used for new project assessments, technique development and quality control / quality assurance (QA/QC) purposes. There would be little impact on the current staffing levels, but more on the overall strategic direction of the facility.

In terms of capital expenditures

- The MLAs must be replaced within the next few years; however they remain operable at the present time. A Field Emission Gun (FEG) system is recommended in a new instrument based on its improved imaging capabilities and reduced down-time for filament changes. Also an instrument fitted with a WDS detector for lower limit elemental detection would be a valuable tool, but would require a highly skilled operator not currently on staff. The overall choice of system type (MLA, QemSCAN, TIMA, Mineralogic) must be evaluated at the time of purchase, as the technology and vendor positions are changing rapidly. Purchase of one new system may suffice for the reduced on-going project needs, given the low utilization of the current MLA instruments.

- The Panalytical XRD is a sturdy unit that can last for many more years, but may require a service contract to ensure availability.
• A fully automated polishing unit, such as the Vanguard or Hexamatic should be considered when the time has come to replace the Struers units.

Based on the industry downturn and ART’s cost-constrained budget, the timing of these capital expenditures can be deferred for the present, but if one of the instruments fails, a decision will be required to either purchase, or make alternate arrangements. Achieving results without key instrumentation however, will move forward via an out-sourcing scenario.

Given the consuming needs of the union staff, it is recommended that a supervisor be appointed or hired to manage the human resource, training and work scheduling requirements for the ART (and AM) technicians, thus freeing up the technical staff to provide value to the company. The on-going problems with the union relating to the AM group, and the current impasse barring trained mineralogists from using mineralogical tools, must be resolved for the future of the group, otherwise Scenario 1 will be the practical result.

The ART mineralogists will continue to develop their relationships with external automated mineralogy service providers. They will provide the technical liaison between Teck customers and their requirements and the service providers. As noted in Scenario 1, out-sourcing must be managed effectively, with appropriate QA/QC and oversight. The mineralogists will also be actively engaged in evaluation of new technologies such as the hyperspectral scanning techniques currently being marketed by the larger commercial laboratories. They should also increase their skill base to provide modelling of large mineralogical datasets, either for metallurgical purposes, or within the geological block models.

This option has a much lower overall capital outlay than Scenario 2, and is less immediately disruptive than Scenario 1. It will, however, move ART AM and Teck to increased reliance on commercial vendors, but allow for the more strategic use of the ART AM technical abilities at a time when CAPEX and OPEX are limited.
4.1.4. Comments

It must be stressed that any 5-year plan for applied mineralogy currently is inexorably linked to the 5-year plan of ART itself, which has not yet been formulated. A review of the ART facility and its strategic direction within Teck is overdue. ART’s technical project mix has transformed over the past 10 years from one dominated by Teck’s base metal operations, to a blend of base metal, coal and energy projects, and for the past two years has been involved heavily with water treatment concerns for the Elk Valley coal operations. ART has a history of providing technical support in the areas most critical to company, be they the HydroZinc project of the early 2000s when zinc prices were at an all-time low, or new process development for the Fort Hills project, Teck’s first oil sands venture. Currently, ART is providing technical expertise and project management to the large, expensive water treatment efforts that must be completed in very short order and are critical to the company’s future.

The 10-year evolution of ART has had both positive and negative impacts on the applied mineralogy group. On the positive side, the broad range of projects has allowed for development of a strong technical competency, but on the negative side, the group has declined from the recent shift of focus from the base metal operations onto water treatment. Budgets have been tightened to meet the water treatment projects, and staff has been re-deployed. This change has similarly impacted the CuZn group within ART, and has been observed by the Teck base metal customers who raise concerns if there will be future capacity at ART to meet their technical needs. At present, there is no acting Section Leader for either the CuZn group or Applied Mineralogy. A strong leader, along with Corporate support is required if these initiatives are to be successful moving forward.

4.2. ART AM – A 5-Year Plan

4.2.1. Scenario Analysis Review

Scenarios 1 and 2 present extreme and opposing visions for ART AM moving forward, and both are disruptive of the current business model at ART.
• Scenario 1 proposes full out-sourcing of applied mineralogy testing to take advantage of the large capacity and excellent pricing available at commercial laboratories. Based on a Porter’s 5-Forces analysis this is optimal solution. It ends the difficulty in providing this service within ART, improves capital efficiency and better allows the technical resources, specifically the mineralogists and metallurgists, to utilize mineralogical data to provide value to projects.

• Scenario 2 proposes expansion and upgrading of the ART AM facility to meet all of Teck’s needs. This makes poor business sense, based on the large capacity currently available in the market, and even less sense given the present challenges of providing the service at ART. The large Capex, Opex and logistical requirements of this scenario are especially non-attractive in the present, cash-constrained mining economy.

• Scenario 3 proposes a re-alignment of the current ART AM business model to begin to develop strategic relationships with commercial service providers and manage the out-sourcing of Teck’s project work, while continuing to have a small on-site instrument base, ideally upgraded when capital is available, for key projects, trouble-shooting and QA/QC. The mineralogists will increase their presence in Teck project teams, their utilization of large data sets and the evaluation of new technologies.

Scenario 3 is deemed the best path forward for the next 5 years at ART. It blends Scenario 1, which highlights the need for increased strategic out-sourcing of mineralogical testing, with the current ART AM business model where data is acquired for key projects, and causes the least disruption of the current work force.

4.2.2. 5 Year AM Budget

Moving ahead, the ART AM 5-year plan proposed here recognizes that both Opex, in terms of staffing, and Capex, in terms of instrument upgrades, are severely constrained at present and for, at least, the next one to two years. It is difficult to predict
how long it will take for the mining industry downturn to end, so the 5-year plan, shown in Table 4-1 and pictorially in Figure 4-4, is quite conservative.

### Table 4-1  Projected 5 Year Budget and Costs for the AM Group

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<tbody>
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<td>Budget</td>
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<tr>
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<td>$115,473</td>
</tr>
<tr>
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<td>$1,050,000</td>
<td>$1,102,500</td>
<td>$1,157,625</td>
<td>$1,215,506</td>
</tr>
</tbody>
</table>

The ART 2015 project budget for applied mineralogical projects, not including mining engineering-related projects, was planned at CAN$1.3M. This number has been retained for 2016 and increases at 5% thereafter.

![Figure 4-4 5-Year Breakdown of AM Facility Development](image)

### 4.2.3. Projects and Technical Focus

The process mineralogy and ore characterization projects will continue over this period for Teck customers. Projects will be critically reviewed for the possibility for out-
sourcing. Development of open service contracts should be obtained for SGS, ALS and BV to expedite future project requirements. A QA/QC protocol for out-sourcing must be developed. Mineralogists should focus attention on the development of new technologies, particularly the new hyperspectral applications and their interactions with site and project customers. Conference attendance is highly recommended, as the ART facility is quite isolated. There is a general need for skills upgrading, and appropriate opportunities should be investigated. Skills in the modelling of large data sets, particularly into three dimensions for resource models should be developed.

4.2.4. Capex

Instrument replacements are earmarked for 2016 (VanGuard or similar automated polishing system), 2017 (MLA or other automated system), 2018 (XRD) and 2019 (second polishing system). There is a possibility that the replacement of the second MLA unit may be required before 2020. If this occurs, a revised strategy of either corporate financing or out-sourcing must be considered.

4.2.5. Opex

The group Section Leader or a Principal Mineralogist role should be filled by 2016 adding an additional Person on Roll (POR) to the team from the current complement of six. Another technical specialist, perhaps in the area of environmental mineralogy or coal mineralogy should be hired later in the 5-year period to enhance the technical mix of the group. It is recommended that a supervisor be appointed for the entire group of technicians at ART, including those in mineralogy. This will facilitate the travel and project time needed by the mineralogists and perhaps improve the on-going labour relations issues.

Service contracts on the instruments and software will be maintained. It is anticipated that there will be continued budget pressure in keeping technician numbers down. OPEX costs for outsourcing will need to be discussed with respect to owner, either corporate, as per current model, or operation.
4.2.6. Alignment

Applied Mineralogy is a core technical competency for Teck Resources. As such it is recommended that AM reside, in terms of reporting lines, within the Teck Corporate sphere, and be linked with the geologists of the Exploration Group and the geologist and metallurgists of the New Projects Group (Figure 4-5). The company should appoint a Chief Mineralogist or similar title, through the corporate office, responsible for the effective development of the out-sourced contracts, and develop linkages with appropriate project teams.

Figure 4-5 Revised organization structure showing optimal placement of AM.
Chapter 5. Recommendations

Based on this strategic business case analysis for the Applied Mineralogy group at ART, the following recommendations are offered for a 5-year plan (2016 – 2020).

- The group will continue to develop its relationships with Teck mine site customers, but also become more closely aligned with the corporate exploration and projects groups. Ideally AM should report to a corporate VP, similar to the Technology VP of 2008.

- Strategic relationships will be pursued with commercial vendors of automated mineralogy services. The ART mineralogists will provide the technical liaison between Teck customers and their requirements and these service providers.

- An effective model for out-sourcing, including QA/QC and oversight must be developed to ensure effective service delivery.

- The corporate ART AM facility will have a small, upgraded instrument base to be used for new project assessments, technique development and quality control / quality assurance (QA/QC) purposes.

- Instrument upgrading will be sensitive to the economic climate and is proposed to be staggered over the 5-year period. The choice of automated mineralogy systems should be critically reviewed at a time nearer to purchase, given the technology flux. Automation of sample polishing should be implemented.
• Mineralogists should place renewed focus on assessment of new technologies and their application at Teck, such as looking for opportunities in hyperspectral scanning.

• Mineralogists should expand their skills to deal with the modelling of large data sets. Software such as LeapFrog and IoGas should be used for data analysis.

• Mineralogists should spend more time on value-add technical programs and communicating with Teck customers and less time on the day-to-day distractions at ART. This would be greatly facilitated by the appointment of a technician supervisor to handle human resource, safety and scheduling needs.

• The group should expand their technical depth later in the period by hiring an environmental mineralogist or a coal mineralogist.
References


Appendix A. Automated Sample Preparation

FLSmidth® QCX/RoboLab®

The addition of the QCX/RoboLab facility expands the capabilities of the newly established state-of-the-art Ore Characterization and Process Mineralogy (OCPM) laboratory in the FLSmidth Minerals Testing and Research Center.

The QCX/RoboLab system in Salt Lake City is capable of processing 200 samples per day, with each sample up to 15 kg and up to 110 mm particle size. The sample types that will be processed in the lab include blast holes, reverse circulation rejects, drill core, bulk ore and ore variance composites. All software and sample preparation equipment in the laboratory is manufactured by FLSmidth.


Figure A1. Buehler Vanguard 2000

Buehler Vanguard 2000

Fully automatic, 6 platen system. Prepares up to 6 specimens at a time in single or central force. Includes dispensing system, ultrasonic cleaner and specimen dryer, 50 method programmability.

https://shop.buehler.com/equipment/grindingpolishing-equipment
Figure A2. Buehler Vanguard 2000. The price of this system in June 2015 is CAN$75,000.

**Struers Hexamatic**

Hexamatic is the most versatile automatic preparation system available, handling both specimen holders for fixed specimens and specimen mover plates for individual specimen preparation. The automatic preparation flow makes Hexamatic the ideal choice for high volume preparation of similar materials. Furthermore, Hexamatic features a possible nine preparation steps, making the total automation perfect for the preparation of a range of materials that require different preparation methods.

[http://www.struers.com](http://www.struers.com)

Figure A3. Stuers Hexamatic
Appendix B. Automated Mineralogy


A laboratory-based, automated petrography analyzer, initially developed for the mining industry, the QEMSCAN 650 serves mineralogy petrology and metallurgy use cases in a wide range of natural resources industries, including mining, oil and gas, and geoscience institutes.

http://www.fei.com/natural-resources/ore-characterization/

Figure B1. QEMSCAN 650. The price of this system in 2012 was CAN$720K.

FEI: MLA - Mineral Liberation Analyzer

A laboratory-based, automated petrography analyzer, the MLA 650 was initially developed for the mining industry. It serves mineralogy, petrology and metallurgy use cases in a range of natural resources industries, including mining and geoscience institutes.
Figure B2. MLA 650 / MLA 650F (FEG). The price of the MLA 650 in 2012 was CAN$920K. The FEG system was approximately $200K higher.

MLA Express

Delivering advanced automated mineralogy analysis from a desktop system at a fraction of the price and operating cost of conventional systems, MLA Express makes this technology accessible and affordable to a broader range of operations.

Figure B3. MLA 650 / MLA 650F (FEG). Pricing is still being developed, but the system is in the range of CAN$300K to CAN$400K.
Tescan: TIMA™ Mineral Analyzer

The TESCAN Integrated Mineral Analyzer. TIMA, a fully automated, high throughput, analytical scanning electron microscope is designed specifically for the mining and minerals processing industry. The TIMA solution will address applications such as Mineral Liberation Analysis, TESCAN, a world leading manufacturer of scanning electron microscopes and focused ion beam workstations has introduced the TESCAN Integrated Mineral Analyzer.


Figure B4. Tescan TIMA.

Tescan: TIMA™ Mineral Analyzer – Automated Loading System

With the newly developed Automated Loading System (AutoLoader), the TIMA has become the first automated mineral analyzer which permits robust, continuous and unattended sample loading. With the AutoLoader (robotics) system which allows accommodation of up to 100 epoxy blocks of 25mm or 30 mm diameter at one time, the TIMA has emerged as a powerful plant support instrument. It increases the sample throughput, minimizes manual labor and enables 24/7 operations. It can be used in daily, continuous mineralogy for mine geology/ore control, concentrators, leach operations, and smelter support. It will also increase the capabilities of technical service centers for mining companies, commercial laboratories, large drilling programs or pilot test campaigns. In combination with a highly automated sample preparation lab (sizing, potting and polishing), TIMA technology can establish high throughput and fast-turnaround automated mineralogy lab modules for mine-site production support.
Zeiss: Mineralogic Mining

Mineralogic is a dedicated automated mineralogy engine designed to run on any ZEISS SEM with multiple integrated EDX detectors. Industry specific modules for the Oil and Gas and Mining industries then allow you to quickly and simply interrogate your data, produce reports and gain unique insights. Characterize minerals and achieve maximum recovery of resources. With Mineralogic Mining you use automated mineral analysis to identify and quantify minerals in real-time. Mineralogic Mining combines a scanning electron microscope with one or more EDS detectors, a mineral analysis engine and the Mining software plug-in. Mineralogic Mining provides industry specific outputs to enhance extractive processes and give operators a leading edge in recovery.

Figure B6. Zeiss Mineralogic System.
Appendix C. Other Mineralogical Instruments

Panalytical - X Pert3 Powder

X’Pert³ Powder is PANalytical’s newest X-ray diffraction system based on the fully renewed X’Pert platform. With new on-board control electronics, compliance with the latest and most stringent X-ray and motion safety norms, advances in eco-friendliness and reliability the X’Pert³ Powder is ready for the future. The system offers an affordable solution for high-throughput, high-quality phase identification and quantification, residual stress analysis, grazing incidence diffraction, X-ray reflectometry, small-angle X-ray scattering, pair distribution function analysis and non-ambient diffraction.

http://www.panalytical.com/XPert3-Powder.htm

Figure C1. Panalytical XPert3 Powder Diffractometer. This system was quoted in 2012 as CAN$140K.

Bruker – D8 / D8 Advanced

The new D8 ADVANCE ECO is the latest member of the comprehensive D8 XRD product family. It combines the proven high performance of the D8 series with easy extendibility and upgradability.

The new D8 ADVANCE ECO is the latest member of the comprehensive D8 XRD product family. It combines the proven high performance of the D8 series with easy extendibility and upgradability.

Zeiss - Xradia 520 Versa

ZEISS Xradia 520 Versa 3D X-ray microscope unlocks new degrees of flexibility for scientific discovery. Building on industry-best resolution and contrast, Xradia 520 Versa expands the boundaries of non-destructive imaging for breakthrough flexibility and discernment critical to your research. Innovative contrast and acquisition techniques free you to seek—and find—what you've never seen before to move beyond exploration and achieve discovery. Xradia 520 Versa achieves spatial resolution of 0.7 µm and minimum achievable voxel of 70 nm.


Figure C4. Zeiss Xradia 520 Versa X-ray Microscope (tomograph)

Bruker Skyscan

The SkyScan 2140 extends the boundaries of non-destructive 3D imaging by adding true 3D chemical analysis capabilities to high resolution microtomography. It combines in one instrument a micro-CT scanner, which provides high-resolution morphological information and absorption correction maps for chemical analysis and a full-field 3D micro-XRF scanner for reconstruction of 3D chemical composition inside the sample.

• 2D energy-dispersive detector acquires distribution for all chemical elements simultaneously. • All chemical elements from Chlorine to Uranium can be detected. • Co-registered 3D micro-morphology and 3D chemical composition. • List-mode acquisition allows reconstructing additional chemical elements without rescanning

http://www.bruker-microct.com/products/2140.htm
Figure C5. Buehler Skyscan (tomograph). The price of this unit in 2013 was ~US$200K.

CoreSCAN MarkIII

Corescan’s Hyperspectral Core Imager Mark III (HCI-3) integrates high resolution reflectance spectroscopy (0.5mm), visual imagery (0.05mm) and 3D laser profiling to map mineralogy and geochemistry related to multiple exploitation phases from greenfield exploration through to ore processing and mine optimization.


Figure C6. CoreSCAN MarkIII
HyLogger

Our hyperspectral logging technology or HyLogging system, characterizes minerals in drill core samples, and is helping the industry improve the efficiency of this process.

The HyLogger is largely automated and driven by a robotic sampling system. It uses visible and infrared light to characterize selected minerals from drill cores, chips and pulps that are often difficult or impossible for human observers to interpret correctly.

Reflected light from the samples is broken into hundreds of different wavelengths by several spectrometers, allowing the recognition of unique spectral signatures for each mineral. Although visible and infrared spectrometers have existed in university laboratories for years, our version is faster, more rugged, automated and supported by special purpose software. The software generates digital images, surface profiles and mineralogical interpretations


Figure C7. CSIRO HyLogger