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Resources for the Future: Challenges and Contradictions

The Mighty Bushveld - Integrating Many Layers of New Ideas

Fine Wines and Terroir in the High Lands of Brazil

The GSC: Older than Canada itself, but still looking ahead

Quebec 2019 – Field Trips for Converging Geoscientists

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Cover Image: The Canadian icebreaker Louis St. Laurent and the Swedish icebreaker Oden, near the North Pole in 2016. The GSC helped to lead this international scientific survey expedition to this remote region. Lebel (this issue) discusses the past and future of the GSC, which marked its 175th birthday in 2017. Photo credit: Asa Lindgen.

PRESIDENTIAL ADDRESS

Sustainable Resources for Generations: The Challenges and Some of the Contradictions

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PREAMBLE

The Resources for Generations (RFG) Conference of 2018 was an important new venture for Canada's diverse Earth Sciences and Natural Resources sectors, and I am delighted that GAC played an important role in its development and successful implementation. I am equally delighted to have delivered the Geological Association of Canada's Presidential Address for 2018 at RFG to my colleagues, friends, mentors and hopefully also to future leaders who I have yet to meet. It has been an honour to be GAC's President for the past year and I hope that all who attended the conference had a great experience at this multidisciplinary gathering. When I started working on RFG 2018 with Dr. John Thompson (RFG Chair), he said something that has stuck with me ever since:

> *"I believe conferences like RFG have the potential to fundamentally change how we develop our natural resources."*

I naturally agreed with John quickly on this general point, but as I became more involved in the planning of the conference the more I came to understand what he meant, and the more I believed this vision to be true. As usual, John was a step ahead of me! In this article, based loosely on the verbal address of June 18, 2018, I will try to address an important theme from the conference, i.e. the question of "Resources for Future Generations." This theme speaks not only to the science that we employ today in the Natural Resources sector, but also to the concept of *Sustainability* in its broadest possible context.

We all know the definition of 'Sustainability,' as articulated in the 1987 Brundtland report entitled "Our Common Future:"

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

I personally think this is a brilliant definition, but it is not always followed literally. In particular, with all the politics and lobbying that arises around any Natural Resources development, we tend to forget that the approach must include both present needs and anticipated future needs. In this article, I will put forward some perspectives on Sustainability as a principle, and its linkages with Geoscience. These include some things that are obvious and self-evident, but also others that may not come to mind so readily. These perspectives are personal, but they come from much experience with the challenges involved in advancing the responsible development of natural resources, particularly in northern Canada. It is probable that not all involved in this sector will agree fully with some of my opinions, and I acknowledge that some represent rather specific concerns and/or interests, but they are put forward with the intent of generating some debate, which I think all will agree is needed. I will start the article with some divergent views from several GAC Past Presidents, and then focus on the state and sustainability performance of the minerals industry (as it relates to current practices), and conclude with some perspectives on the role of Geoscience in this goal of providing "Resources for Future Generations," while also respecting and preserving our precious natural environments.

ABOUT 'RESOURCES FOR GENERATIONS 2018' – WHAT DID IT INCLUDE?

RFG 2018 was one of the first international conferences in Canada "*dedicated to the availability and delivery of resources to sustain future generations*." (John Thompson, Letter of Invitation from the Chair, RFG 2018 Steering Committee). RFG 2018 had six major themes – Energy, Minerals, Water, Earth, Resources for Society, and Education. These are all critical components for sustaining our current standard of living and for the future well-being of our children. In Canada, we find ourselves in a situation where knowledge, technology, science and engineering are increasingly integrated and capable of providing innovative solutions for sustainable development of our natural resources. However, the importance of public opinion and support is increasingly critical in this objective, and this popular influence on decision makers can have a profound effect on the approval and successful execution of major industrial projects. RFG was an ambitious conference and will hopefully help set a path that will result in the long-term and sustainable development of our natural resources and improve our overall performance as a country. Many of my comments in this article relate to the minerals industry (in the broadest context) as

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most of my own career has been involved in this part of natural resources extraction. However, the general principles apply, at least in part, to all sectors involving non-renewable resources, and some that exploit renewable resources.

Some of the Vision Statements associated with RFG 2018 include:

- Humans will need a range of natural resources, including energy, minerals and water, to survive and prosper for the foreseeable future.
- Humans will increasingly value their environment from global to local scales as they appreciate the impact that environmental degradation has on human lives and other species.
- Research across the full spectrum of Earth Science, and related areas of Engineering and Technology, will play vital roles in advancing understanding and use of natural resources.
- Indigenous people have a unique history and valuable knowledge related to natural resources and the environment that must be understood.
- Listening to different views and seeking understanding will provide a basis for a better future.

These points are highly insightful and speak volumes of where we are as a society in Canada, and they outline the challenges we face as a country in maintaining and further building our natural resources base. The key message is simple: *Nation building is becoming more difficult and more complex.*

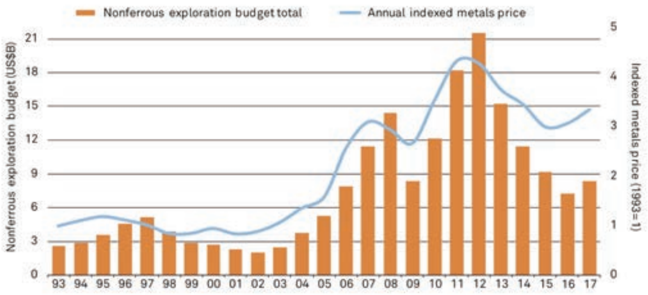
CHALLENGES IN NATURAL RESOURCE DEVELOPMENT: THE RELEVANCE OF EARTH SCIENCES

Gone are the days when a minerals company could stake claims, assess the resources and economics of a deposit and then reliably predict when licenses, permits and authorities might be granted for mining development. I know from first-hand experience that in any due diligence evaluation of a mine acquisition proposal, the *permitting risk* (in the broadest context) is one of the greatest factors in determining if a merger or acquisition will or will not proceed. The elevated permitting risk that the minerals industry is experiencing across Canada is one of the most significant issues that the industry is facing in the 21st century, and it has the potential to negatively affect international investment in our country.

I consider myself primarily an Environmental Manager with a geological background. The vast majority of my career has been spent solving problems that arise between Natural Resources development and the environmental, socio-economic and cultural issues that are seen, sometimes automatically, to be in conflict with them. I have found this role to be enormously satisfying over the past 40 years by providing solutions to reconcile seemingly polarized viewpoints. In this context, my background as an Earth Scientist has proved incredibly helpful. I therefore feel that I have some background and experience in these key areas of RFG and strongly feel that the statement John made about the future of Natural Resource development is true; *we need to fundamentally change the approaches that we have inherited from previous generations if we are to meet the needs of future generations.* The second key message is longer than the first, but in essence just as simple: *Sustainability may be achieved by effective collaboration, transparency and information sharing, improved knowledge and clear actions by all involved, working together in an integrated manner.*

During the preparation of this address, I reached out to GAC Past Presidents and other leaders to get some comments around the RFG 2018 theme and how Earth Sciences can contribute to this important subject. The following are some memorable quotes that I would like to pass along for consideration. Please note, I have not included all the material that I received and that at times I have provided some additional thoughts and imposed some 'editorial license.' Nevertheless, the collective wisdom of several Past Presidents was very important for the development of this address, and I offer many thanks to all for their influential thoughts.

- In spite of massive education and information, and the significant influence of social media supporting conservation of resources and sustainable goals, energy and resource consumption is *not* decreasing. Increasing demand means a *continued* need to extract, modify and produce products for consumers and global economies.
- The provision of resources (energy, minerals and water) for the future is one of several critical issues along with climate change, ocean pollution and management of hazards, which are fundamental to human survival and prosperity.
- All of our challenges are underpinned by a knowledge of Earth Science, but most people have a limited appreciation or understanding of the relationships between solving such challenges and the need for scientific understanding.
- Canada is a 'Resource Nation' benefiting from our geology and the extent of our landmass; however, we are also the world's highest per-capita consumers of energy and minerals. Therefore, the contribution that Earth Science can make to discovery, responsible extraction and use of these natural resources is incredibly important.
- Given the Paris Climate Agreement (and background studies), we need to reduce and replace many of the conventional resources that we are currently using; however, this will take time and the approach must be balanced.
- Continued over-population is resulting in massive migration to cities and urban areas, which will put tremendous pressure on local resources such as water and land.
- We need to educate current and future generations about natural resources so that they understand more about the economics and value of these resources, the environmental impact of their extraction, and about the fact that they are not infinite.
- Geoscience plays an increasingly critical role in our society. Whether it is helping to ensure our health, to secure our heritage, to enhance our wealth, or to augment our security, geoscience affects all aspects of our lives. We do this work in the Earth Sciences to protect our water, to cope with our climate, to support construction, to deal with toxic substances, to manage our waste, to prepare for hazards, to



Date as of January 31, 2018.
Source: S&P Global Market Intelligence

Figure 1. Trends in global exploration spending for nonferrous metals from 1993 to 2017, as compiled by S & P Market Intelligence (2018). Note that the estimates are in dollars of the day, and are not corrected to account for inflation.

ensure our supply of energy and materials, to know and protect our land, to survey and manage our oceans, to understand the history of life, and to comprehend our planet Earth.

- Earth Scientists are best placed to understand the balance among economy, ecology and environment needed to sustain civil society and the natural systems upon which it relies.
- In recent years, the effects of Earth processes, such as earthquakes, landslide, subsidence, and floods, are communicated around the world in a matter of minutes. Society can and should make much better use of our knowledge of Earth's surface makeup and processes to better avoid or minimize natural disaster effects, especially with the dramatic changes associated with the effects of climate change.

So, there we have it. These quotes and thoughts are not attributed to specific individuals, although some appear in previous Presidential Addresses. They have something in common, in that they state that Earth Scientists have a unique training and experience to assess, predict and help manage the sustainable development of our natural resources in the context of environmental management and mitigation of climate change. Some also imply that we have an innate talent for this. But do we?

EXAMPLES OF CHALLENGES IN THE MINERALS RESOURCE SECTOR

It is instructive to review how the development of mineral resources has evolved and changed over the past few decades and to highlight not only the challenges, but also the incredible progress that has been made in Natural Resources development. For a general summary of the state of global mining and exploration, I present here some interesting and instructive charts and statistics extracted from "World Exploration Trends," published by S&P Global Market Intelligence in March 2018 (see Figs. 1 and 2).

- Global spending for the exploration of nonferrous metals increased in 2017 to $ 8.4 billion from $ 7.3 billion (US) in 2016. This is a significant jump of some 15% following a five-year decline and represents the most significant increase in investment since 2013.
- The main focus of exploration has been on gold with some improvements on base metals, although this is not apparent from the general trend shown in Figure 1.
- The prediction for 2018 is that exploration spending will increase by a further 15–20% over the year. However, there continues to be significant market volatility that could have a negative impact on future exploration investment.
- Metal prices continue to trend upward due to an improved global economy and a weaker US dollar.
- Canada and Australia are the global leaders for exploration investment at some 14% each for nonferrous exploration budgets.

These points clearly show a positive global investment trend for minerals exploration, but at the same time producing mining companies appear to be cutting their exploration budgets. Is Canada ready to benefit from this improving global exploration investment market? Are we in a position to maintain a positive investment climate, but at the same time keep sustainability as an important goal of Natural Resource developments?

SCIENCE, ENGINEERING, OUTREACH, AND THE PERMITTING PROCESS

Earlier in this article, I mentioned that I consider myself largely to be an Environmental Manager. In this role, and in varied capacities, I have been involved in the approval and permitting of almost every new mine development across northern Canada over the past 40 years. In my experience, every successful mine approval in northern Canada since the mid-1990s has had the following attributes:

- Rigorous science and engineering has been the core of approvals. Both industry and government (including Assessment Boards) hire consultants to ensure an expert level of review of any mine development proposals. This sometimes leads to 'disagreeing' experts, but it also provides for the development of common ground and solutions for all parties.
- Environmental assessment and regulatory approvals are completely transparent. All stakeholders, First Nations governments and other federal and provincial/territorial governments, as well as the general public, are given the opportunity to fully participate in the process(es). This includes documentation such as "Reasons for Decisions," Public Registries and participation in technical workshops, public meetings, and a fair hearing process. Open communications are maintained throughout the decision-making process. Northern Canada provides a good example where environmental assessment is based on co-management boards that employ a transparent process to drive the review and approval of projects.
- Mineral development proponents are held to account for their environmental and social/cultural performance through a rigorous environmental assessment and regulato-

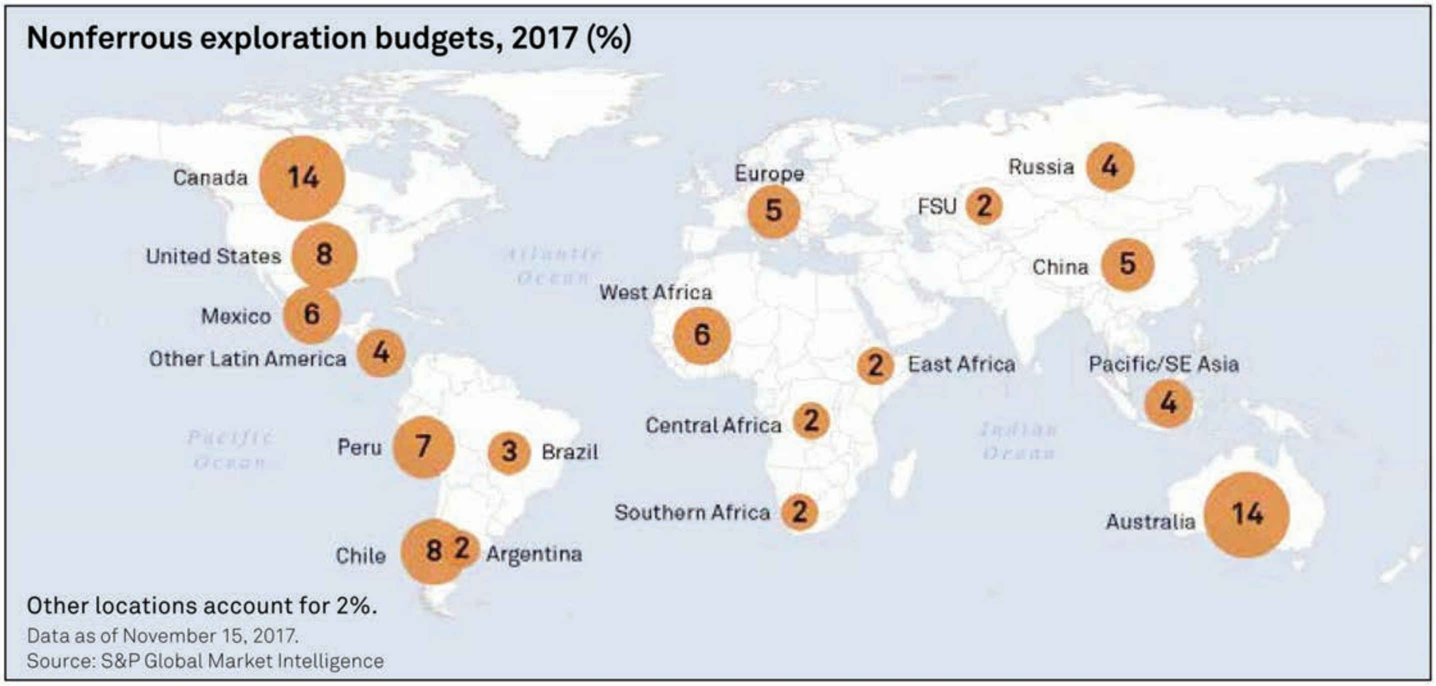


Figure 2. The global distribution of exploration expenditures for nonferrous metals in 2017, as compiled by S & P Market Intelligence (2018).

ry approvals system. For example, a mine development proposal can require over 200 approvals *after* a multi-year environmental assessment process. It is important to note that environmental assessment was at one time limited to a planning process intended to provide guidance for the issuance of licenses and was required only for projects that received federal funding. In today's world, approvals of mine development projects from start to finish (including both environmental assessment and subsequent regulatory approvals) can take at a minimum 3 years, and many require more than 10 years.

The approval process for mining projects does not always end with a positive decision. Also, there have been numerous court actions over the past 20 years that challenged the decisions made during these approval processes, and these litigations have added to investment uncertainty in Canada.

Indigenous issues and concerns have become incredibly important for Canada and the minerals industry has worked very hard to improve their engagement and consultation practices, as well as to develop fundamental partnerships with First Nations communities and their government structures. This has resulted in a mosaic of agreements, such as Cooperation Agreements and Impacts and Benefits Agreements (IBAs) across the country, which start at the exploration stage and then follow right through to production. These types of agreements include training and employment opportunities, environmental monitoring, traditional knowledge studies and protocols, cash payments, capacity building, royalties and others. The map in Figure 3 shows the extent of active agreements across Canada. Although the full details may not be apparent from this summary map, it indicates that this aspect of Natural Resource development is now almost universal.

In summary, Canada has one of the most transparent and rigorous approvals systems in the world for Natural Resources proposals, such as mines, pipelines and hydro projects. Nevertheless, it is clear from observations that this process is far from simple and far from getting simpler. New mining projects are inevitably beset by controversy. This brings us to another key message: *Why is there still so much controversy when new mining projects are proposed, and how can geoscientists help to ensure that discussions and decisions reflect accurate science and not misinformation?*

PERCEPTIONS AND MISPERCEPTIONS IN RESOURCE DEVELOPMENT

When was the last time that the media reported a positive public reaction to a mining project? It simply does not happen. But why is this so?

The approvals process for mining projects has improved dramatically over the past 30 years and the environmental and social performance of the minerals industry has also improved dramatically. The preceding section shows that the current environmental assessment and regulatory approvals process is rigorous, thorough, expensive and, above all, inclusive. Yet there remains a perception out there that Canada cannot make decisions over major projects in a timely and progressive manner. Why is this?

- Perhaps it is generally accepted by the general public that government decisions and their institutions cannot be trusted.
- Perhaps Non-Governmental Organizations (NGOs) have provided such a strong voice to oppose such projects that a larger (but silent) supporting constituency may have no effective voice.

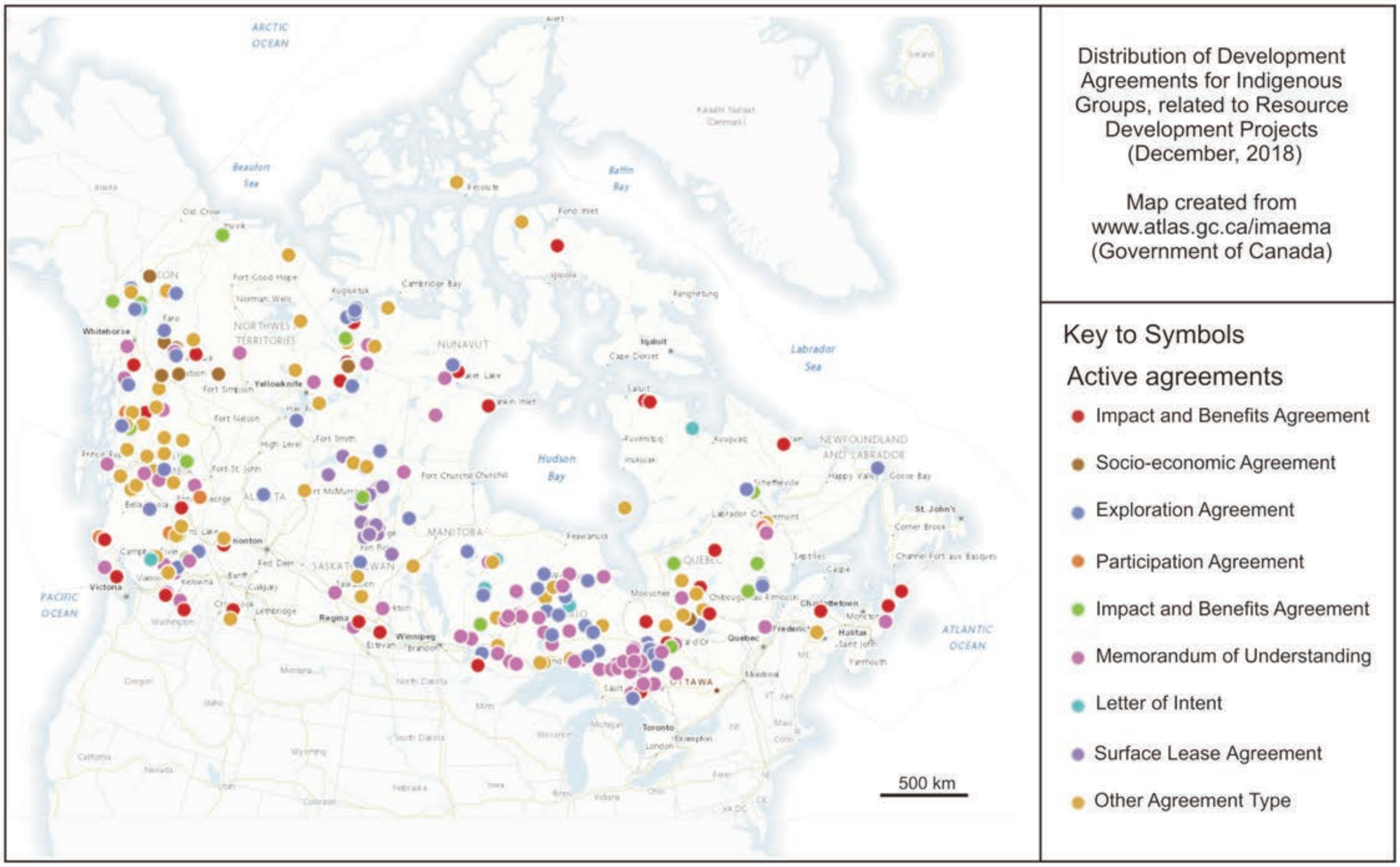


Figure 3. A summary map showing the diverse locations and nature of negotiated agreements with indigenous peoples across Canada; published online by the Government of Canada, Department of Indigenous Affairs and Northern Development (www.aadnc-aandc.ca).

- Perhaps the magnitude of societal benefits, and the rigour associated with the approval and management of modern Natural Resources projects over their life cycle has not been effectively communicated to all stakeholders.
- Perhaps society is simply going through a 'cynical' phase in which little or nothing is believed in the face of so-called 'fake news' and increasing governance through tweets rather than reasoned statements that include explanations.

Whatever the exact reason, we continue to experience challenging times with regard to the public perception of Natural Resources projects. However, I believe that we are well down the road to achieving sustainability due to the improved performance of both government and industry. The example of the minerals industry is instructive, and it leads us to another key message: *It is incredibly difficult to permit any Natural Resources Project in Canada and it should be difficult.*

ADDRESSING THE CHALLENGES – A ROLE FOR GEOSCIENTISTS

Canada is blessed with natural resources that have provided us with economic certainty and comfort, even in times of widespread global recession such as the global financial crisis of 2008–09. We need to keep developing such natural resources in a sustainable and thoughtful manner, and must build our natural resources inventory to meet the demands of the future, including renewable energy sources. We need to be constantly improving our performance in mineral exploration, in responsible Natural Resources development and in the mitigation of the environmental and socioeconomic impacts that accompany such projects. How can Earth Sciences and indeed science in general help with the above challenges?

The following is a great comment provided by former GAC President Stephen Johnston (personal communication, 2018) that I consider most appropriate as a framework for closing this address:

> *"We are continuing to educate and train excellent Earth Scientists. Today's students are going out and doing a better job than ever before of combining traditional 'geological' knowledge with cutting-edge technology in order to find and develop energy, minerals and water resources. But it is no longer enough for Universities to churn out 'geologists' aimed entirely at resource development. We cannot continue to send geologists into industry without them understanding the Earth System and unable to speak to the challenges presented by global warming and our role in climate change. University professors cannot continue to view their role as simply educating the next generation of Earth Scientists. We have to turn our attention to educating not just our students, but also the public at large for society to face up to the challenge of providing*

> *our children and their children and all future generations with safe and responsible natural resources projects."*

I think this says it all. Our youth are charged with the responsibility of not only being great geoscientists in the traditional sense but also the much broader challenge of being stewards of the Earth, and demanding that all Natural Resources development be carried out in a sustainable manner. This will require continued and systematic financial support from government and a 're-thinking' of how we train our Earth Sciences students. Skills such as managing risk, effects assessment, communications, facilitation and mediation and understanding other perspectives through listening will be critical for future government and business leadership.

I also believe that we must do a much better job at integrating geoscience disciplines at the university level to equip our youth for the professional world. For example, there are strong environmental linkages between host-rock mineralogy, surface water and groundwater processes, Quaternary stratigraphy and geochemistry in terms of metal leaching and acid-rock drainage. The latter, commonly abbreviated to ARD, is central to many challenges to mine approvals centred upon their potential impacts beyond extraction sites. A trained geoscientist with a strong grounding on the science and linkages can provide a more reliable prediction of environmental effects to assess this issue, and implement appropriate mitigation and monitoring. This is just one example of how there is a need to connect subjects that are often taught in artificial isolation.

I have always found that my geoscience background gives me a tremendous advantage in managing the environmental assessment process and regulatory approval of mine development proposals. There is perhaps no subject in which so many disciplines connect in unexpected ways, or in which an understanding of time-scales beyond those of humanity are so important. This leads me to a final set of three key messages that cannot and should not be seen in isolation.

- *Integrated Geoscience is required to provide the necessary scientific support for wise decisions with Natural Resources development. Universities and colleges have the responsibility to critically look at themselves and how they train our future geoscience leaders.*
- *Geoscientists have the future challenge of "building our reputation and social license" like our mentors – Logan, Dawson, Fortier and Bostock, to name just a few. They had this in the form of strong support of their expeditions that were so fundamental in building our country.*
- *Geoscience has a strong role within the national dialogue around Natural Resources development, and how this fits into a world struggling with climate change, water shortages, pressures on land usage and maintaining relationships with Indigenous peoples. Geoscience can provide integrated solutions for a wider effort to facilitate the change to renewable energy sources that is needed for the future maintenance of global climates.*

CONCLUSIONS

Amongst the several key messages that I have tried to convey in this article, the following points are perhaps the most important as conclusions.

Firstly, Natural Resources development must keep raising the performance bar to achieve true sustainability over the long term. Secondly, although we are on the right path towards this goal, there remain many clouds on the horizon. Irrational politics in an increasingly polarized world could easily take us off the track of investing wisely and considering the long-term impacts of short-term decisions. This may seem to be a strong statement but I believe it is a real concern, particularly for the western world, and particularly if the consensus of science is ignored. Thirdly, effective communication is required amongst *all* stakeholders to ensure there is a balanced debate about new Natural Resources projects that are so important for the future of Canada. Last, but certainly not least, geoscience and geoscientists have critical roles in providing leadership for the assessment and approval of future Natural Resources projects.

The members of the Geological Association of Canada will be well aware of many of the issues discussed in this address, and many will understand the challenges that societies such as ours face in a world in which demographics, priorities and the nature of careers are changing more rapidly than ever. Organizations such as ours have a critical role to play in addressing many of the challenges noted in this article, and it is very important that they remain (or become) active, healthy, inclusive and especially more youthful. I have enjoyed my year as President of the Geological Association of Canada, and hope to contribute more to it in years to come. There is much room to contribute through us to the wider growth of geoscience in Canada, and it is ever more important to see our discipline as an integrated whole rather than several specialist clans that sometimes compete when we should really cooperate to realize a wider vision of what we do and why it is so important.

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SERIES

Igneous Rock Associations 23. The Bushveld Complex, South Africa: New Insights and Paradigms

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SUMMARY

The Bushveld Complex has continued to serve as the basis for study into the fundamental nature of petrological processes for layered intrusion formation and for oxide and sulphide-hosted Platinum Group Element (PGE)–Cu–Ni ore deposits. These studies have included discoveries in terms of the physical extent of Bushveld magmatism, both laterally and internally. Lateral variations in the mafic to ultramafic Rustenburg Layered Suite of the Northern Lobe of the complex have also revealed petrologically distinctive Upper Critical Zone equivalent rocks (the so-called Flatreef) with enhanced contamination and mineralization traits that reflect a transition between Eastern and Western Lobe equivalent stratigraphy and Platreef-style complexity. Traditional magma mixing models have been re-examined in light of radiogenic isotopic evidence for crustal involvement early in the chromite precipitation or formation process, combined with evidence for associated heterogeneous fluid contents, cryptic layering profiles, and textural evidence. A wide variety of alternative ore-genesis models have been proposed as a consequence. The fundamental mechanics of magma chamber processes and the existence of the magma chamber as an entity have been called into question through various lines of evidence which have promoted the concept of progressive emplacement of the complex as a stack of not-necessarily-quite-sequentially intruded sills (with or without significant quantities of transported phenocrysts), emplaced into variably crystallized and compacted crystal-liquid mush mixtures, modified by compaction-driven late magmatic fluid (silicate and aqueous) activity. Alternatively, petrological and geochemical observations have been used to discount these interpretations in favour of more conventional cooling and gravity-driven accumulation of silicate and ore minerals in a large, liquid-dominated system.

RÉSUMÉ

Le complexe de Bushveld a demeuré à la base d’études sur la nature fondamentale des processus pétrologiques de formation d’intrusions litées et des gîtes des éléments du groupe platine (ÉGP)-Cu-Ni hébergés dans les oxydes et les sulfures. Ces études ont comporté des découvertes sur l’étendue physique, à la fois latérale et interne, du magmatisme de Bushveld. Les variations latérales de la suite stratifiée et mafique à ultramafique Rustenburg du lobe nord du complexe ont également révélé des roches équivalentes pétrologiquement distinctes de la zone critique supérieure (le communément désigné Flatreef) avec des traits de contamination et de minéralisation accrus qui reflètent une transition entre la stratigraphie équivalente des lobes est et ouest et la complexité de type Platreef. Les modèles traditionnels de mélanges magmatiques ont été réexaminés à la lumière de preuves isotopiques radiogéniques indiquant une implication de la croûte au début du processus de précipitation ou de formation de la chromite, combinées à des preuves de contenu fluide hétérogène associé, de profils de litage cryptique et de preuves texturales. Ainsi, une grande variété de modèles alternatifs de genèse de minerai a été proposée. La mécanique fondamentale des processus de la chambre magmatique et l'existence de la chambre magmatique en tant qu'entité ont été remises en question au moyen de divers éléments de preuve qui ont mis en avant le concept de mise en place progressive du complexe sous forme d'un empilement non-nécessairement séquentiel de sills injectés (avec ou sans quantités significatives de phénocristaux transportés) mis en place dans des mélanges de bouillie cristaux/liquide à cristallisation et compaction variable, modifiés par une activité tardive de fluide

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magmatique (silicaté et aqueux) induite par la compaction. Alternativement, des observations pétrologiques et géochimiques ont été utilisées pour écarter ces interprétations en faveur d'un processus plus conventionnel de refroidissement et d'accumulation de minérais silicatés et minéralisés induite par la gravité dans un vaste système à dominance liquide.

Traduit par la Traductrice

INTRODUCTION

The Bushveld Complex (or Bushveld Igneous Complex, BIC), hosted in northeastern South Africa, represents the world's largest known layered mafic intrusive complex, and the largest magmatic ore resource (Lee 1996; Viljoen 2016), containing significant proportions of the Earth's known extractable ores of Platinum Group Elements (PGE), Cr, and V, along with other subsidiary magmatic and contact metamorphic (andalusite, specifically) ores. The Bushveld has been the subject of geological study since 1872, evidently having engendered on the order of 200 publications by the 1930s (Eales 2014), on the order of a thousand by the 1970s (see Cawthorn 2015; p. 521), and thousands since then (nearly 3000 publications since 1994 contain 'Bushveld Complex' in their titles, based on a quick online search, including about 500 in just the past four years). This review does not, therefore, purport to represent an overview of the existing knowledge on the Complex, which is in a constant state of flux and has been usefully summarized in the relatively recent past by authors including von Gruenewaldt et al. (1985), Eales and Cawthorn (1996), Cawthorn (2015), and Viljoen (2016), for example. A particularly useful review of the key aspects of genetic models for mineralization and relevant igneous processes was published by Maier et al. (2013), and an introductory level, less technical overview has also been provided recently by Eales (2014). The reader seeking supplementary accounts of the detailed characteristics of the Complex is also directed to works such as these.

The Bushveld Complex includes, in approximate order of emplacement, the bimodal volcanic rocks of the Rooiberg Group (Hatton and Schweitzer 1995), the ultramafic to mafic rocks of the Rustenburg Layered Suite (RLS), and the granitic intrusive rocks of the Lebowa Granite Suite (see Eales and Cawthorn 1996, and references therein). For the purposes of this review, the term Bushveld Complex is being used here with specific reference to the rocks of the Rustenburg Layered Suite, unless otherwise noted. In spite of the plethora of research on the Bushveld Complex over its history, a wide range of extremely fundamental questions remain unresolved and under active investigation over the last decade or two. Many of these questions have arisen as a consequence of improvements in analytical resolution or access to previously inaccessible types of data, while others have arisen as a consequence of detailed mapping and the extrapolation and development of new ideas. Unresolved questions include such basic elements as the original extent of the vertical and lateral stratigraphy of the BIC, the nature of the parent magmas, the basic manner of emplacement of the constituents of the complex, the triggering and concentrating mechanisms for the Cr–Fe oxide, PGE-sulphide, and Fe–Ti–V oxide ores, each of which have their own set of models, and the fundamental tectonic justification for the existence of the BIC. In this review the concepts relating to the Bushveld Complex have been presented in the following categories, in which there have been significant developments which have helped to resolve long-standing issues, or more often, to introduce new concepts which undermine traditional paradigms in igneous petrology and magmatic ore petrogenesis:

- the basic stratigraphy of the BIC
- ore deposit models applied to the BIC
- the nature of the parent magma to metalliferous rocks
- constraints on contamination of BIC magmas
- emplacement processes for BIC rocks

A simplified geological map and stratigraphic column are provided as Figures 1 and 2, respectively. The Critical Zone, overlying the Lower Zone, features the presence of discrete horizons of chromitite, associated with rhythmic modal layering in the Upper Critical Zone, which is distinguished from the Lower Critical Zone by the presence of cumulate (primocryst) plagioclase in the former. The chromitite layers range from cm- to metre-scale thicknesses, and provide economic quantities of chrome ores. The chromitite layers are hosted within harzburgite and pyroxenite in the Lower Critical Zone, supplemented and/or replaced by (increasingly poikilitic upwards) leuconorite to anorthositic and noritic layers in the Upper Critical Zone. Most of the chromitite horizons are enriched in PGE relative to the silicate rocks, and the PGE are largely present as platinum-group minerals (e.g. Kinloch 1982; Junge et al. 2016), although disseminated sulphide minerals and PGE are not strictly restricted to the oxide horizons. The chromitite layers are designated as LG (Lower Group) chromitite, numbered from 1–7 upwards, then MG (Middle Group), within which sequence the Upper Critical Zone commences, and finally the UG (Upper Group) chromitite layers, which include the distinctively bifurcated and multi-layered UG-1, the PGE-rich UG-2, and capped by the PGE-rich Merensky Reef. The Merensky Reef is itself overlain by a PGE-poor lithological sequence which otherwise virtually replicates the Merensky sequence, which is hence known as the Bastard unit. Overlying this is the Main Zone, featuring the appearance of primocryst clinopyroxenes (both pigeonite, now inverted, and augite). Near the top of the Main Zone is the so-called Pyroxenite Marker (which varies lithologically around the complex). The Main Zone is overlain by the Upper Zone, which features an increasingly ferrogabbroic sequence interrupted by a suite of Fe-Ti oxide layers (at least 21 of them) dominated by magnetite with subsidiary ilmenite and ulvospinel, and economic grades of vanadium, decreasing in grade upwards through the sequence. The top of the Main Zone features apatite-rich dioritic rocks, grading into what has been proposed as the Roof Zone granophyric rocks (Cawthorn 2013), which represent the interactive zone between Bushveld differentiates and the Rooiberg volcanic rocks (Hatton and Schweitzer 1995), which serve as the roof to the BIC.

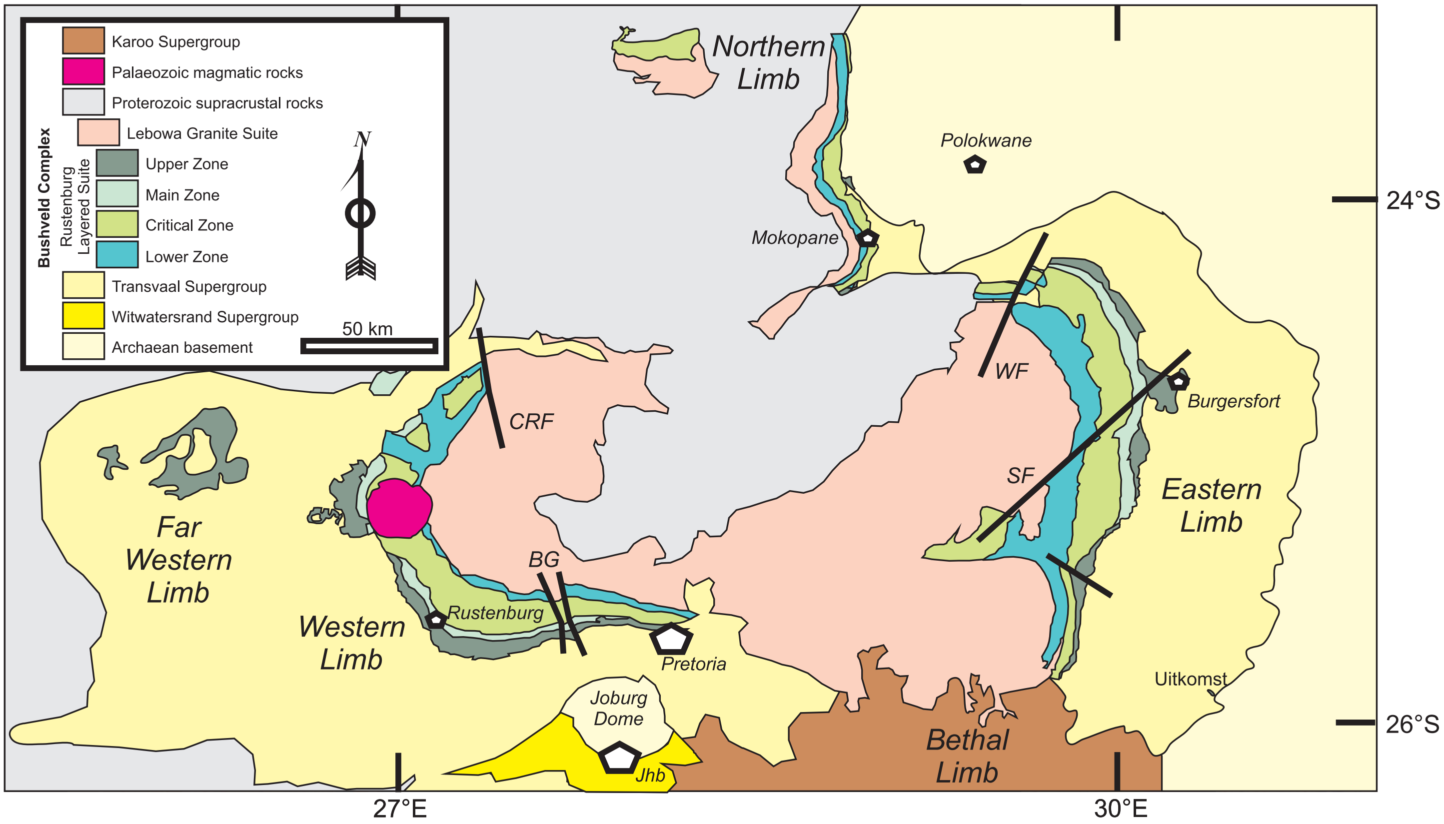

Figure 1. Simplified geological map of the Bushveld Complex and geographically associated rocks. Jhb = Johannesburg. Adapted from Johnson and Wolmarans (2008). Positions of crustal lineaments and/or faults (solid lines transecting the Rustenburg Layered Suite -RLS) after Cawthorn (2006) and Maier et al. (2013). BG = Brits Graben; CRF = Crocodile River Fault; SF = Steelpoort Fault; WF = Wonderkop Fault; Joburg Dome = Johannesburg Dome.

EXTENT OF BUSHVELD MAFIC MAGMATISM

The total thickness of the sequence in the Eastern Limb is ca. 8100 m, as compared to around 7220 m in the Western Limb (Eales and Cawthorn 1996). A distinguishing feature of the suite is the remarkable lateral continuity of the modal layering, particularly of the oxide layers, which can be traced and correlated for tens to hundreds of kilometres across the complex with relatively little systematic change in character over large lateral distances. Any genetic model for their formation is constrained by this trait. Only the eastern and western limbs feature these thicknesses of relatively complete lithological sections through the complex. The Bethal Limb appears to reflect mostly Upper Zone rocks, while the Far Western Limb features Lower Zone equivalents. The Northern Limb was mapped (van der Merwe 1978) as featuring Upper and Main Zone lithologies only, with Lower Zone equivalents present as discrete bodies hosted within the footwall, and until relatively recently, it was understood that Critical Zone magmas and the resultant rhythmically layered sequences and laterally continuous chromitite layers were not present there (Kruger 2005).

Recent drilling in the northeastern part of the Eastern Limb (the so-called Clapham Section) has revealed a new and significant magmatic sequence below the Lower and Marginal Zones (i.e. the putative base of the Bushveld sequence), such that an additional 750 m or so of primitive ultramafic rocks has been identified, summarized in Figure 3. This sequence, which is similar to the Lower Zone in terms of lithological assemblages, has been named the Basal Ultramafic Succession (BUS) by Wilson (2015), who distinguished it from the overlying Lower Zone, from which it is separated by the Marginal Zone rocks. This sequence also features a ca. 1 m thick contact chilled zone against the floor quartzite, as well as additional chilled units, spinifex-textured and harrisitic-textured rocks in the lowermost 100 metres. Wilson (2015) has proposed that this represents the earliest and most primitive Bushveld material to be injected into the upper crust. It remains to be seen how extensive and/or representative this unit may prove to be. Sharpe and Hulbert (1985) reported chilled ultramafic sill textures from the eastern lobe, but it is perhaps noteworthy that recent work in the Northern Limb has also shown extensive thicknesses of putative Lower Zone ultramafic rocks typically lying below (rather than above, although this is also described) the Marginal Zone norite and feldspathic pyroxenite (Yudovskaya et al. 2013b). In addition, Maier et al. (2016) have reported spinifex-textured komatiitic marginal chilled rocks from the western Bushveld.

Other Bushveld-type Magmatism

In addition to these main constituents of the BIC, compositional equivalents have been identified farther to the west and to the east. To the west, in Botswana, the Molopo Farms Complex constitutes an additional 30% of the surface area of the

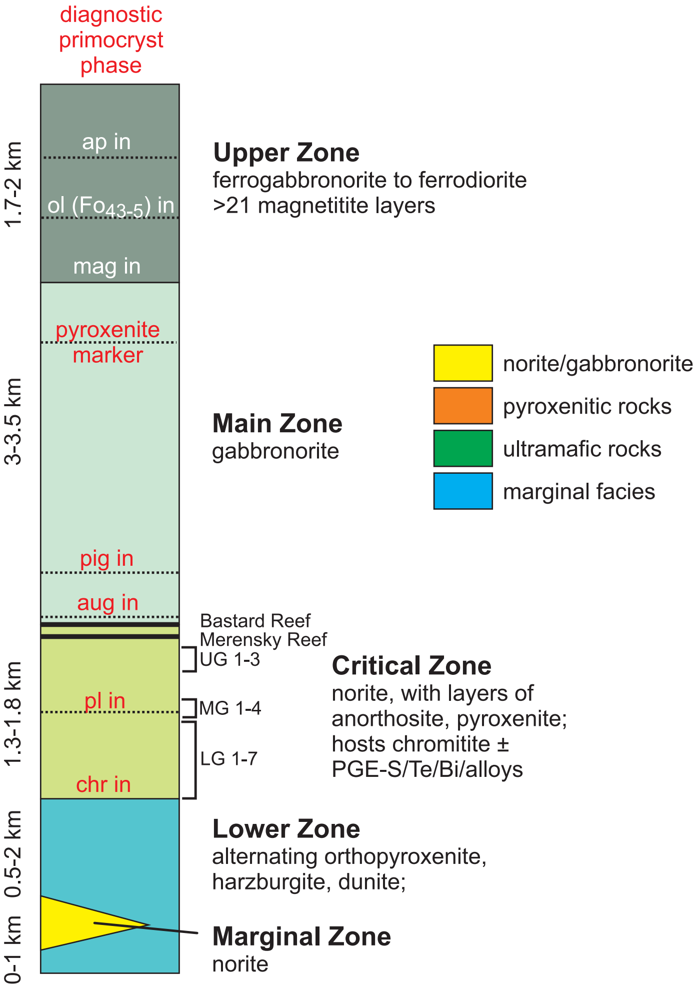

Figure 2. Simplified stratigraphy of the Bushveld Complex, showing the main lithostratigraphic zones and their associated ore horizons, modified after Eales and Cawthorn (1996), Cawthorn (2006) and Wilson (2012).
The thickness of individual zones and/or subzones varies across and within lobes; the typical ranges are shown here.
ap = apatite; ol = olivine; mag = magnetite; pig = pigeonite; aug = augite; pl = plagioclase feldspar; chr = chromite.
The two main cumulus minerals whose disappearances are noteworthy are chromite, which ceases at the top of the Critical Zone, and olivine. Olivine's occurrence is intermittent in the Lower Zone and Lower Critical Zone, and then it reappears intermittently in association with specific mineralized reefs higher in the Critical Zone, in somewhat anomalous circumstances. It should not, therefore, be treated as a persistent cumulus/cotectic mineral over this whole interval.

Bushveld, albeit occurring entirely in the subsurface and consequently relatively poorly studied. A poorly-constrained Rb-Sr age published in prospecting reports suggests that the intrusion is contemporaneous with the BIC (usefully summarized in Kaavera et al. 2018). Prendergast (2012) suggested that the Molopo Farms Complex was derived from magmatic equivalents to the ultramafic Bushveld Lower Zone, and hence is not a strong prospect for either Critical Zone nor Platreef-style (Northern Limb) sulphide mineralization. However, Kaavera et al. (2018) suggested that rocks consistent with the putative parental magmas to Bushveld rocks of the Lower and Main (but not the Critical) Zones are all identifiable within the Molopo Farms stratigraphy, such that rather than the Molopo

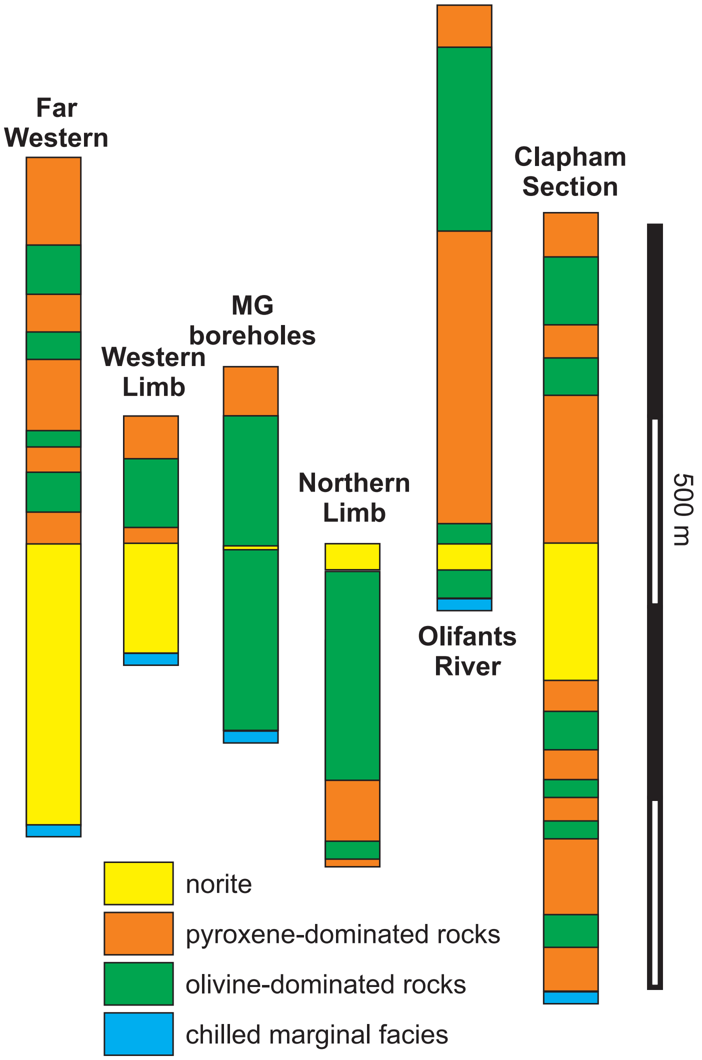

Figure 3. The stratigraphy of the Lower and Marginal Zones of the Bushveld Complex, in simplified sections from west to east, using the Shelter Norite of the so-called Marginal Zone as the index horizon. Modified after Wilson (2012).

Farms being a residual Lower Zone equivalent only (Figure 4), it is rather a more complete Bushveld magmatic equivalent but with a distinct (more rapid) crystallization history.

Gauert (2001) suggested that the Uitkomst was a conduit or feeder to a now-eroded (or otherwise undiscovered) Bushveld-like body to the east, rather than having fed the Bushveld Complex proper to the northwest (Figure 5), consistent with geometric factors (the sill is tilted upwards to the southeast), but mainly based on geochemical criteria such as timing of contamination, cumulate extraction and sulphur saturation. Eales and Cawthorn (1996) reported several other small but less well studied Bushveld-equivalent bodies hosted in footwall rocks within about 50 km of the known sections, in various directions.

Geophysical Evidence for Interconnectivity of Lobes

One of the long-standing fundamental aspects relating to the mafic magmatism (the RLS) in the Bushveld is whether the exposed lobes are in fact interconnected at depth. The review

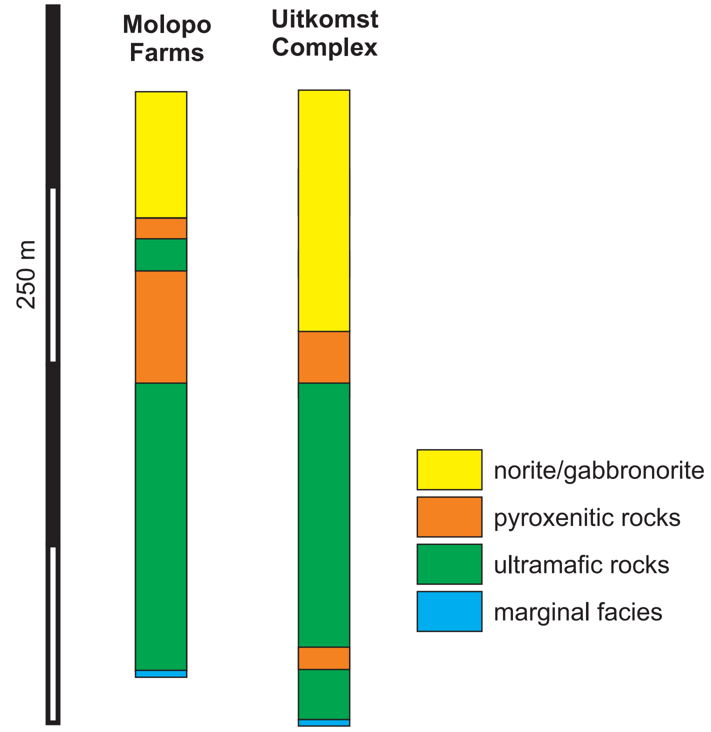

Figure 4. Simplified stratigraphic sections of the Molopo Farms and Uitkomst complexes, coeval intrusive complexes with Bushveld-like magma compositions. See text for additional information. Molopo stratigraphy modified after Kaavera et al. (2018) and Uitkomst after Maier et al. (2018).

by Cole et al. (2014) usefully summarized the history of interpretation of the geophysical evidence over the past 60 years, wherein Cousins (1959) interpreted the RLS as representing two entirely independent intrusive bodies, apparently flying in the face of the geological interpretations offered over the first half of the 1900s in which the complex was depicted as a laterally continuous, inwards-dipping lithological package. The subsequent geophysical interpretation by Meyer and de Beer (1987) incorporated the geological criteria but also determined that there were insufficient grounds to justify the presence of a buried mass of mafic to ultramafic rocks in the interior of the complex.

More recently, Webb et al. (2004) and a series of follow-up studies have established a relatively good fit between modelled and observed gravity field measurements across the complex (Fig. 6) by incorporating revised data and interpretations of the thickness and density of the crust, particularly those of Nguuri et al. (2001), Nair et al. (2006) and Kgaswane et al. (2012), and the density of the mantle, across the section. Cole et al. (2014) demonstrated that as a consequence, the BIC is best modelled as a set of interconnected lobes, as opposed to separate inwards-dipping sheets. This interpretation is consistent with the findings of unspecified drilling reported in Eales and Cawthorn (1996), which has revealed Lower Zone-equivalent rocks at depth beneath granite and sedimentary rocks in the interior of the complex, and with the identification of Bushveld-type Critical Zone-like rocks as xenoliths found in the Palmietgtat kimberlite pipe (Webb et al. 2011), which has intruded the interior of the complex.

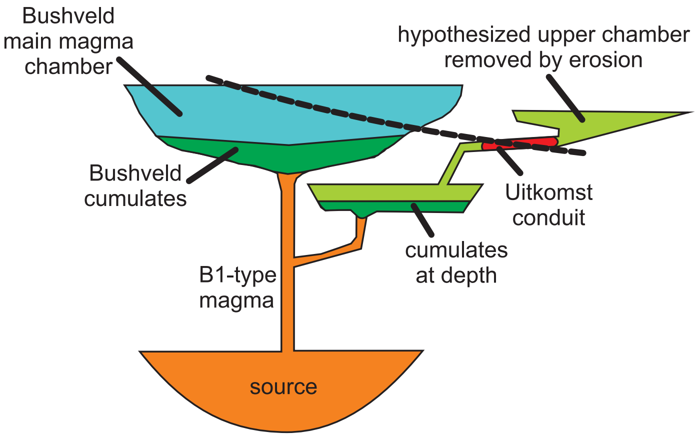

Figure 5. Simplified model of the genetic relationship between the Bushveld and the Uitkomst complexes. The dashed line indicates the current erosional level. Modified after Gauert (2001); see text for discussion.

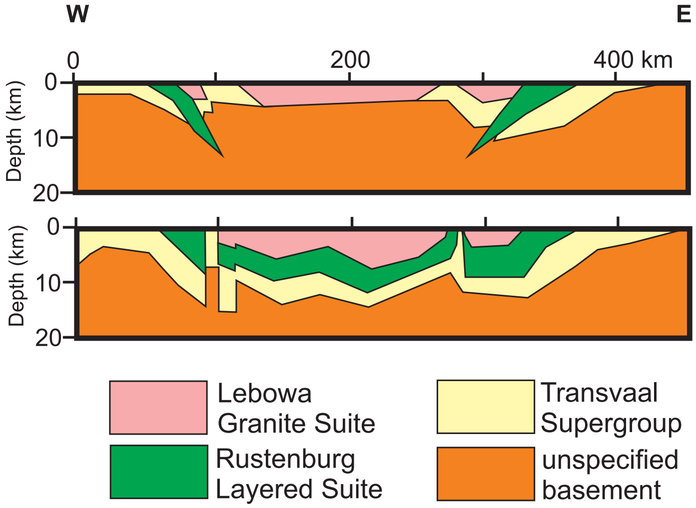

Figure 6. Geophysical models for the Bushveld Complex, contrasting the old, dipping but separate lobes model above, and the recent, revised contiguous stratigraphy model below. See text for discussion. Modified after Webb et al. (2011).

Although Cawthorn (2015) indicated concerns with some of the evidence for specific prospective feeders, there appear to be no real issues with the concept of multiple injection or intrusion sites. The implication is then that magma derived from a common, deeper source was injected into the shallow crystal-liquid pile that was the nascent RLS, and experienced similar (nearly identical) circumstances across the entire breadth of the intrusion in order to generate broadly correlative suites of oxide (chromitite or magnetitite) layers and associated sulphide minerals in a broadly similarly well-correlated lithologic sequence of silicate rocks. Therefore, any process proposed as an explanation for the associated oxide and sulphide layers must take into account the lateral continuity required for such a process. This will be referred to more specifically in the section relating to oxide reef petrogenesis below.

ORE DEPOSIT MODELS

Although not an issue necessarily specific to the Bushveld Complex, the association of disseminated sulphide minerals with the oxide reefs (both chromitite and magnetitite types) is well established (e.g. Lee 1996; Naldrett 2004; Naldrett et al. 2009) and as a consequence underpins many of the genetic models for these horizons. The crustal contamination model originally proposed by Irvine (1975) as a mechanism for inducing the *in situ* formation of chromitite layers in mafic to ultramafic intrusions has been seen as particularly appealing, since crustal contamination is widely applied as a trigger for sulphur saturation and the formation of sulphide liquids in layered intrusions (e.g. Li and Naldrett 1993; Naldrett 2004). The apparent congruence of these models with the physical evidence for crustal contributions associated with the oxide (specifically the chromitite) layers has contributed to the appeal of the crustal contamination model.

The variant of the model proposed by Campbell and Turner (1986) involves upwards-pluming of the incoming magma and subsequent turbulent interaction with granitoid roof rocks to create a hybrid magma from which chromite precipitated and was subsequently deposited elsewhere. Evidence includes the association of more radiogenic Sr and Nd with chromitite horizons (e.g. Kruger 1994; Kinnaird et al. 2002), although the precise nature of the spatial relationship between isotopic enrichments and chromitite is inconsistent. The most comprehensive study published so far is that by Kinnaird et al. (2002) in which transects were taken across a variety of chromitite layers in the eastern and western lobes, and including Lower and Upper Critical Zone rocks. Data from selected chromitite layers are shown in Figure 7, selected based on examples where there were relatively tight sampling intervals from footwall, chromitite reef, and hangingwall rocks.

NATURE OF PARENT MAGMA AND METAL BUDGET IMPLICATIONS

Chilled Margins and Feeder Dykes

It has been established that the Marginal Zone norite does not represent a chilled marginal facies (Cawthorn et al. 1981), as had been proposed by Wager and Brown (1968), and its origins and relationship to the rest of the BIC rocks remain somewhat enigmatic. Eales and Cawthorn (1996) suggested that these rocks might in fact be intrusive sills. Cawthorn (2015) provided a useful analysis of the norite with regard to Wager and Brown's proposed context. In Figure 8, evidence of local modal mineralogical variation exhibited in Marginal Zone noritic rocks indicate that these rocks have experienced post-emplacement petrological evolution inconsistent with a primary chilled margin. It may be worth observing that apparently stratigraphically anomalous, near-basal, geochemically and isotopically evolved rock layers also occur elsewhere in layered intrusions, such as the microgabbroic unit near the base of the Panzhihua magnetiferous ferrogabbroic intrusion (Howarth and Prevec 2013), which is also characterized by thick oxide ore horizons.

Mapping of sills and dykes in the footwall rocks of the complex in the 1980s allowed for the identification of various suites of broadly basaltic affinity, some of which were identified as prospective feeder dykes to various parts of the Bushveld (Sharpe 1981; Cawthorn et al. 1981; Sharpe and Hulbert 1985). Of particular interest were those proposed to be responsible for the Cr- and PGE-mineralized Critical Zone rocks, which are known as the B1 dykes (parental to the Cr-rich Lower Zone and Lower Critical Zone) and the B2 dykes (parental to the PGE-rich Upper Critical Zone) of Sharpe (1981). Other dykes and/or melt compositions have been proposed for the overlying Main (B3 dykes) and Upper Zones, summarized by Eales and Cawthorn (1996). These dyke compositions continue to be widely applied as reference compositions for Bushveld parent magmas (e.g. Arndt 2005; Maier et al. 2018), but the inferred crystallization sequence and metal budgets in particular remain problematic with the use of tholeiitic compositions. Specifically, the B2 composition, postulated as the parent for the PGE- and chromitite-bearing Upper Critical Zone rocks, is poor in Ni and PGE, and rich in Cu and in high field strength elements such as REE and Y, relative to B1 and B3 compositions (Barnes et al. 2010), and relative to its Cr-budgetary requirements (see below).

Attempts to model the crystallization sequence of a magma of B2 composition, such as using the modelling program PELE of Boudreau (1999) at upper crustal pressures (1–5 kbar) and oxygen fugacities around QFM suggest that orthopyroxene will not occur initially on the liquidus (Barnes et al. 2010), which is inconsistent with the dominantly noritic modes of the Critical Zone rocks, featuring prominently primocrystic (cumulus-textured) orthopyroxene. One possible solution noted by Barnes and Maier (2002) was to model a hybrid magma composition, wherein a 60:40 mixture of B1 and B2 compositions, respectively, could generate the requisite mineral assemblage, consistent with the suggestion of Sharpe and Irvine (1983) in which crystallization sequences appropriate to the Upper Critical Zone were derived through mixing of A (anorthositic) and U (ultramafic, boninitic) magma compositions. Similarly, Li et al. (2005) suggested an equal mixture of the residual liquid from 44% crystallized B1 melt with a B3 (proposed Main Zone parent) liquid to account for the compositions found in the Merensky Reef. It has even been suggested that the B2 composition could in fact represent residual magma (Cawthorn 2007) from which the Critical Zone rocks had already been extracted, rather than a putative parental magma composition, which would be more consistent with the observed depletion in Cr and PGE, as well as the relatively evolved Cu, PGE, and Mg#. This residual magma, if it was indeed such, could not itself have subsequently crystallized as the olivine-free Main Zone, nor from the largely olivine-free Upper Critical Zone, however, as it contains olivine on the liquidus.

In addition to tholeiitic basaltic and boninite-like (Barnes 1989) parental magma compositions having been proposed, contaminated ultramafic parent magmas have been suggested (Sharpe and Irvine 1983; Eales and Costin 2012; Maier et al.

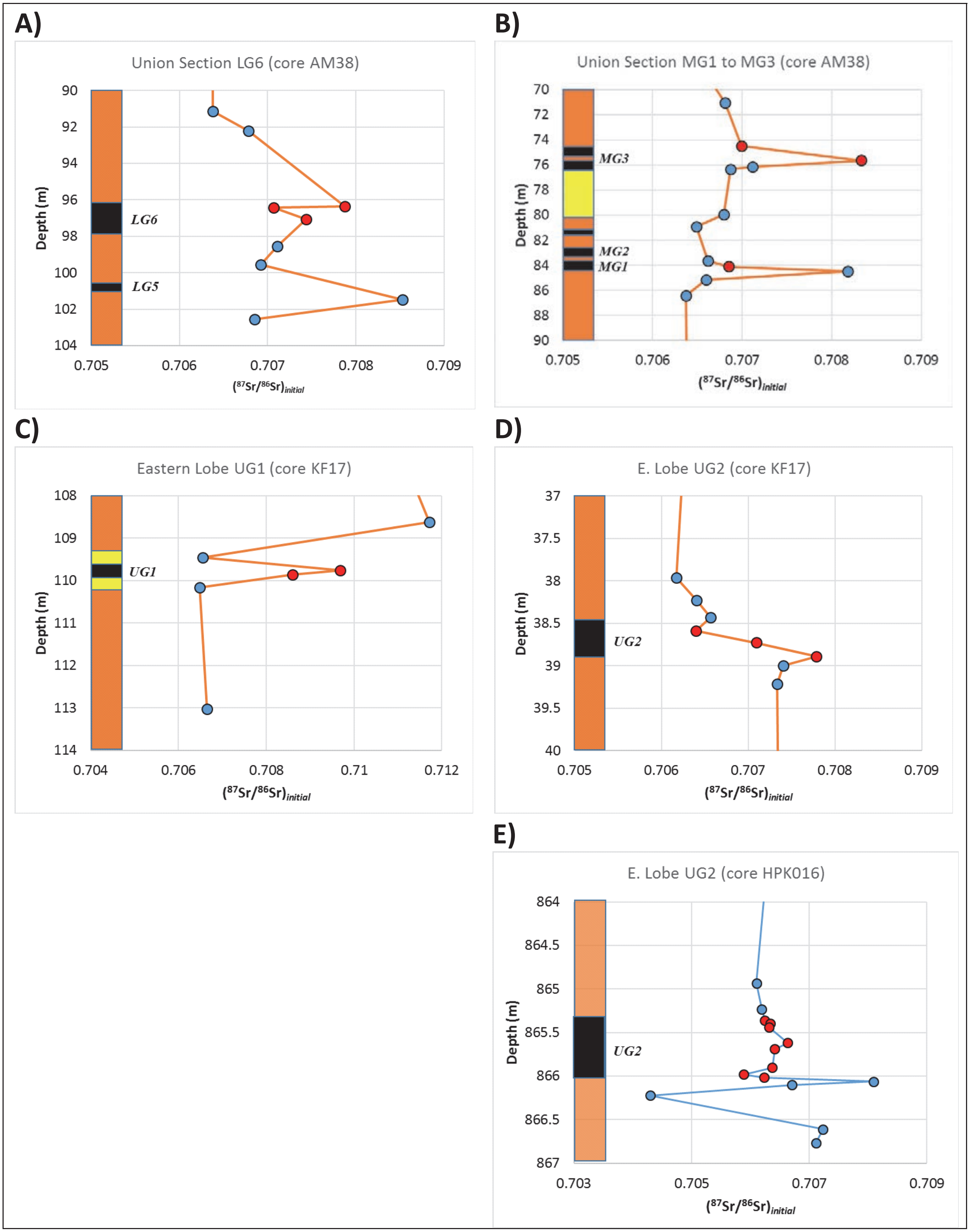

Figure 7. Variations in initial ^{87}Sr/^{86}Sr ratio across various chromitite seams, after Kinnaird et al. (2002) (A–D) and Schannor et al. (2018) (E). Lithological sections along the y-axis include pyroxenite (orange), anorthosite (yellow), and chromitite (black). Data points in red indicate chromitite seams (analyzed as plagioclase mineral separates).

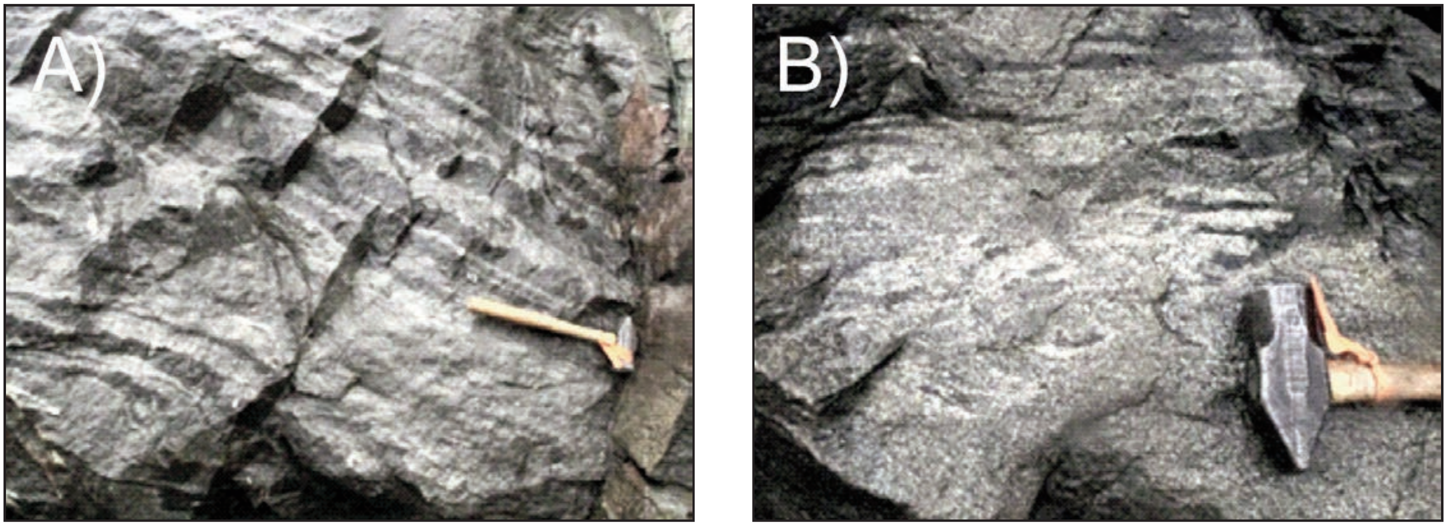

Figure 8. Local modal variation exhibited in the so-called Marginal Zone norite adjacent to the footwall contact, from the Eastern Lobe of the Bushveld, illustrating evidence for mineral fractionation processes. Geological hammer is approximately 35 cm long. A) shows distinct modal layering of pyroxenitic and noritic layers, and local plagioclase-rich segregations. In B), disrupted modal layering is suggestive of a dynamic magmatic environment prior to complete solidification.

2016) in order to provide the combination of contaminated but metalliferous characteristics that appear to be required to explain the metal budgets and bulk compositions, particularly in light of the additional volumes of ultramafic material recently revealed (Wilson 2015). In Table 1 below, the major element compositions of the B1 and B2 dykes are compared with prospective ultramafic compositions that have been proposed.

Metal Budget Constraints

The capability of these magmas to provide sufficient metals, specifically chromium, to meet the requirements of the observed chromium budget of the Lower and Critical Zones of the complex can be simplistically tested. Eales (2000) undertook to estimate the chromium budget of the Western Lobe of the complex, summarized here in Table 2, for which his wt.% Cr_2O_3 data have been converted to Cr (ppm) for ease of reference. Note that Cawthorn (2015; p. 550) discussed the potential oversimplification of Eales' approach to this calculation, but in the absence of alternative estimates, these remain the most useful reference data available to date.

Furthermore, assuming that all Cr was introduced into the Bushveld Complex within Cr-undersaturated parental magmas (i.e. excluding the possibility of transported xenocrystic or phenocrystic chromite grains), the amount of parent magma required to accommodate each of the various zones of the Rustenburg Layered Suite can also be estimated, as displayed in Table 3 (A, B). These calculations indicate that a B2 magma composition would require on the order of 40 km thickness of material to produce the amount of Cr currently observed in the Critical Zone of the Bushveld alone, in stark contrast to the 1.3–1.8 km of Critical Zone currently known (Eales and Cawthorn 1996), or even the 7–9 km total thickness of the complex, if one were to postulate that the metals were extracted from the magma in its entirety (i.e. that one parent magma, albeit with a complex multistage contamination and upper

Table 1. Compositions of proposed parent magmas for the lower, ultramafic to mafic units of the Bushveld Complex.

Element (wt %)	B1	B2	footwall peridotite	contaminated komatiite	B1 chill margin
SiO_2	55.74	50.79	47.35	51.89	56.09
TiO_2	0.34	0.76	0.16	0.4	0.28
Al_2O_3	11.82	15.7	6.12	9.5	11.31
Fe_2O_3*	10.5	12.54	10.11		
FeO				9.43	7.79
Fe_2O_3				1.25	1.53
MnO	0.18	0.19	0.15	0.27	0.17
MgO	11.85	6.91	27.85	18.28	13.58
CaO	6.5	10.7	3.57	7.67	6.34
Na_2O	1.63	1.94	0.63	0.33	1.43
K_2O	0.98	0.25	0.43	0.67	1.05
P_2O_5	0.08	0.16	0.04	0.09	0.07
Cr (ppm)	965	201	5722	1386	1576

B1, B2 and ultramafic footwall sills from Barnes et al. (2010)
Contaminated komatiite from Maier et al. (2016)
B1 chill from Wilson (2012)
Fe_2O_3* = total Fe as Fe_2O_3.

Table 2. Calculated chromium budgets for the Lower and Critical Zones of the Bushveld (after Eales 2000).

Stratigraphic Interval	thickness (m)	average %Cr_2O_3	Cr (ppm)
Upper Zone	1900	<0.01	<68
Upper Main Zone	205	0.03	205
Lower Main Zone	2205	0.02	137
Upper Critical Zone	475	0.88	6021
Lower Critical Zone	785	1.71	11700

Table 3A. Calculated thicknesses of ore-hosting units assuming all chromium was dissolved in the designated parent magma (based on Cr values and unit thicknesses of Eales (2000)).

					parental magma candidate	
Element		**B1**	**B2**	**footwall peridotite**	**contaminated komatiite**	**B1 chill margin**
Cr (ppm)		965	201	5722	1386	1576
Unit	**Thickness (m)**	**Amount of parent (m) required for the observed Cr contents**				
CZ	1,260	12,459	59,816	2,101	8,675	7,629
CZ + LZ	2,080	16,940	81,327	2,857	11,794	10,372
LCZ + LZ	1,605	13,946	66,955	2,352	9,710	8,539

CZ = Critical Zone, LZ = Lower Zone, and LCZ = Lower Critical Zone. Sources as in Tables 1 and 2.

Table 3B. Calculation of parent magma volume required to account for Cr budget (from Table 3A) represented as proportions of the actual reported unit thickness.

Unit	**Thickness (m)**	**Amount of parent, as a factor of unit thickness, required for the observed Cr contents**				
CZ	1,260	9.9	47.5	1.7	6.9	6.1
CZ + LZ	2,080	8.1	39.1	1.4	5.7	5.0
LCZ + LZ	1,605	8.7	41.7	1.5	6.0	5.3
	proposed parent:	**B1**	**B2**	**footwall peridotite**	**contaminated komatiite**	**B1 chill margin**

crustal emplacement history, perhaps largely taking place in sub-crustal settings, was serving as the source for the Rustenburg Layered Suite). Conversely, the B1 magma would only require 8–10 km thickness to produce the required amount of Cr for the whole complex, hosted within the basal 2–3 km, and within the order of magnitude of the total magmatic resource available. Even the postulated ultramafic compositions would require more magma than is currently represented in the existing stratigraphy, but the required volumes are within a factor of six of the observed Cr requirements. The calculated parent magma thicknesses required can also, or alternatively, be expressed as a factor of the measured unit thickness, for ease of analysis, as is shown here in Table 3B. The same budget concerns apply to the PGE, Cu and Ni, as noted by Barnes et al. (2004), for example.

EMPLACEMENT MODELS

The Conduit Model

The conduit model means in effect that no proposed parent magma can easily account for the Cr budget of the Critical Zone entirely transported as dissolved Cr within the incoming magma (i.e. there is no proposed parent magma for which a factor of 1 (or less) times the observed unit thickness can be derived). There are two obvious solutions to this apparent dilemma. One would involve the application of the so-called conduit model, wherein the Bushveld Complex as it is currently preserved would be seen as a cumulate-dominated system through which large volumes of magma had passed (i.e. continental flood basalt), to be extruded or emplaced elsewhere leaving behind a disproportionate volume of residual solids, including cumulate-textured ultramafic rocks and early dense metals (such as chromite and sulphide-hosted ores). The ore deposits and host rocks at Noril'sk (e.g. Naldrett et al. 1995; Arndt 2005), Voisey's Bay (e.g. Li and Naldrett 1999) and Duluth (e.g. Ripley 2014) are generally envisioned as classic examples of this deposit type, as is the Bushveld-affiliated Uitkomst Complex, as has already been described. Cawthorn and Walraven (1998) proposed that on the order of 1.5 km of magma was 'missing' from the complex on the basis of incompatible element budgets (K, Zr), and even larger volumes of Critical Zone magma must be missing in order to meet PGE budgetary requirements predicated on models involving vertical settling of metals from above the most PGE-rich deposits at the top of the Critical Zone (e.g. Cawthorn 2006), namely those of the UG2 and Merensky Reef lithological suites. Cawthorn (2015) noted that given that Critical Zone mineral compositions have been correlated to less than 20% crystallization of the parent magma, this would require five times more magma volume (i.e. five times the existing Critical Zone thickness as residual liquid) to be accounted for. (This deduction excludes the possibility that the residual magma went on to crystallize as any other observed part of the Bushveld Complex.) Li et al. (2005) suggested nearly 50% crystallization of B1 magma to get to the top of the Critical Zone, so with losses for trapped liquid in those cumulates, the 'missing liquid' in this context could conceivably be reduced to a factor of two or less, based on mineral compositional criteria. However, even taking into account large errors due to regional variations in the estimations of metal budgets, unit thicknesses, degree of fractionation, it is clear that the units that currently host the ore deposits cannot have deposited those ores as closed systems. This missing magma would have to have been either erupted or intruded elsewhere laterally (or both); there is currently no evidence of the former, but numerous Bushveld-equivalent laterally-intruded bodies exist, as outlined earlier, albeit none so far identified with Critical or Main Zone geochemical affinities. In addition, the possibly partly coeval lavas (Hatton and Schweitzer 1995) of the Dullstroom Formation of the Rooiberg Group, and the extensive Rooiberg felsites (e.g. Twist and French 1983), as well as the extensive Lebowa Granite Suite (Walraven and Hattingh 1993) cannot be entirely dismissed as potential comagmatic components, in part, at least (Hatton and Sharpe 1989), although these are most likely dominantly crustal partial melts (Hatton 1995; Hatton and Schweitzer 1995) rather than differentiates of basaltic composition source rocks or magmas.

Transported Metals and Slurries

The alternative to a conduit model is the proposition that the metals were introduced to the stratigraphy as transported load, at least in part, but potentially in large part, if the budget calculations above are to be believed, and depending on the parent magma composition proposed. Eales (2000) has suggested that very fine-grained primary chromite, as well as olivine and orthopyroxene, may have been sourced from a more ultramafic subchamber "at depth", from which the solid material could have been transported as a mush or slurry and then redeposited within the upper Bushveld as periodic injections, mixing with the resident residual liquids (Eales 2000; p. 148). He proposed that the chromite could then have been concentrated during deposition by processes including convective scavenging (Rice and von Gruenewaldt 1995), to which the hydraulic sorting process proposed by Maier et al. (2013), may be added, and then subsequently annealed and further concentrated by late magmatic or subsolidus recrystallization and ripening to achieve their current grain size and distribution (Hulbert and von Gruenewaldt 1985). Peridotitic bodies hosted in the footwall (which are otherwise viewed as Lower Zone-like overflows; Sharpe and Hulbert 1985) are presented as possible manifestations of such an injection process.

Some of the main concerns with sourcing either individual lithological or modal layers or packages of rock (i.e. a modally layered cycle or suite) from laterally injected slurries into an existing crystal–liquid mush pile include the ability to transport such layers laterally with great continuity in style and mineralogy and metal grade for tens to hundreds of kilometres, the ability to maintain a suspended load over great distances and then very efficiently sort it, largely by density, upon the cessation of lateral transport, and the presence of vertical cryptic and whole-rock chemical fractionation trends within lithostratigraphic units, which would seem to mitigate against the dumping of a transported crystal mass. Essentially the 'need' for the introduction of metals as transported phenocrysts (fundamentally the metal and cumulate budget imbalance) has led to the motivation for a lateral slurry model, which has then been supported by various petrological lines of evidence, but the mechanical process of emplacement remains the biggest hurdle. Note that while a process of emplacing a slurry created by gravitational collapse and slumping laterally across the transient magma chamber floor, as proposed for the Skaergaard by Wager and Brown (1969) and invoked for the Bushveld by Maier et al. (2013) may involve less resistance from the resident magma-crystal mixture than a forcible lateral intrusion into a semi-solid cumulate pile, the fundamental process controls are similar. If the cumulate pile is entirely solid, it requires other considerations. Cawthorn (2015) devoted about seven pages to critically addressing the concept of laterally-introduced slurries, and his topics include the apparent absence of high-pressure mineral compositions (such as aluminum-rich pyroxene or chromite, which would apply to mantle-derived crystals, less dramatically to crystals forming in crustal plumbing systems, and not at all to wall-collapse-derived slurries), and the isotopic discrepancies between the chromitite layers and their overlying silicate units (as shown in Fig. 7 above) which suggest that they are not obviously cogenetic, among others.

The need to justify metal budgets through injection of phenocryst-rich sills has led to the consideration of the concept of layered intrusions as stacks of sills, emplaced at intervals, and introduced loosely but not precisely sequentially from bottom to top. This concept has been partially laid at the door of Bruce Marsh for his assertions that cumulate layering can only be a product of dumping of transported crystal loads, and not the products of in situ differentiation and fractionation processes (e.g. Marsh 1996, 2006 and 2013), concepts which owe much to studies of crystallizing lava lakes and Antarctic sills, cited in Marsh's work. His models, in contrast to the application of some of these ideas to the Bushveld, are entirely independent of the concepts relating to metal budget imbalances. The concepts attributed to Marsh have been addressed directly (e.g. Latypov 2009; Latypov et al. 2015), and in recent years the discussion has moved specifically to the rocks of the Bushveld Complex, although not so much into the literature in terms of testing models as yet. Assessing the ongoing debate about the validity or relevance of the in situ evolution versus transported phenocrysts concepts to the origins of layered intrusions is beyond the scope of this review, but its application to Bushveld rocks is unavoidable and represents a significant component of the current research discussion. Among other things, there have been petrologically and geochemically-motivated arguments made in support of intrusive origins to either the chromite and PGE-bearing units (e.g. Scoon and Teigler 1994; Naldrett et al. 2012) or the overlying gabbronorite units (e.g. Roelofse and Ashwal 2012), and efforts have been made to assess the mechanical and thermal/temporal restrictions on emplacing the complex as a series of smaller sills, versus fewer larger ones (e.g. Cawthorn 2012). Latypov et al. (2017) also noted that chromitite-bearing units are commonly transected by their overlying hangingwall units in the form of apparently syn-magmatic erosive pothole structures, for example, which would preclude the inversion of the emplacement sequence. For more details on this, a subsequent discussion and reply to this paper has followed thereafter (Scoon and Mitchell 2018; Laytpov et al. 2018a).

In particular, recent precise U–Pb zircon geochronological results (e.g. Mungall et al. 2016) have indicated, controversially, that the zircon closure temperatures reflect non-sequential emplacement of mafic and ultramafic components within the Critical and Lower Main Zones, summarized in Figure 9. At face value (i.e. interpreted as straightforward magmatic crystallization ages corresponding to emplacement), this would appear to require the intrusion of mafic to ultramafic sills into existing semi-solid or arguably solidified mush or hot rock (respectively) sequences of mafic material. The analysis of precisely what cooling conditions are being recorded by the zircon ages, the ability to reproduce these age relationships from different sections of the Bushveld sequence (i.e. both laterally and perhaps vertically), and what mechanical conditions could facilitate such age relationships, have yet to be established. It has been suggested, for example, that late magmatic volatile activity may have had a disproportionate influence on prolonging the cooling of zircon hosted within the lower units of the Critical Zone, as contrasted to zircon near the top of it (Yudovskaya et al. 2013a), based on Ti geothermometric and trace element abundance data in zircon cores and rims, which could influence the interpretation of the newer zircon geochronological evidence.

The volumes or thicknesses of individual pulses within the Bushveld have been speculated upon by various authors, largely model-dependent, such as based on geochemical or radiogenic isotopic characteristics, rather than petrologically dictated in any rigorous mechanically or compositionally modelled way. In Figure 10, some of the proposed dimensions of magma influxes are presented based on Bushveld Critical Zone rocks, where rhythmically layered repetitive suites or cycles have been most prominently described.

The nature of the apparent cyclic rhythmically layered units has been called into question in recent years as well. The fundamental cyclic lithological unit of the Upper Critical Zone may be described as a sequence consistent with density stratification, with an oxide (chromite)-rich base (typically chromitite), overlain by pyroxenite, grading upwards into leuconorite or anorthosite, commonly with a very thin layer of pure anorthosite underlying the next cycle. Each of these cycles occurs on a scale of metres to tens of metres, with varying thicknesses of relatively homogeneous norite separating them. This is highly oversimplified in terms of actual Bushveld stratigraphy, but probably acceptable. Figure 11 illustrates various representative sections across the Merensky Reef from the western and eastern lobes of the Bushveld, demonstrating the inconsistent relationships between the pyroxenite, the chromitite, the pegmatoid units, and the PGE.

The broad modal sequence exhibited is thus generally consistent with traditional crystallization models wherein the relatively early crystallized, first on the liquidus minerals also tend to be the dense ones, so sequences that are sequentially chromite-, orthopyroxene-, and plagioclase-dominated are consistent with both equilibrium crystallization (in principle, if not necessarily in terms of mineral proportions) and with density sorting. This is convenient from the perspective of traditional primary magmatic models for igneous layering (e.g. Naslund and McBirney 1996), and remains the prevalent model for the Bushveld rocks (e.g. Naldrett et al. 2012). However, alternatives to the cyclic rhythmic modal layering model have been proposed for Upper Critical Zone chromitite units in recent years. For example, it has been suggested at various times that the anorthositic 'tops' to rhythmic cycles have been induced by the introduction of hot, dense rocks above them, rather than representing plagioclase-rich 'floats' or crystallization from residual liquids expelled from the underlying cumulates. For example, Nicholson and Mathez (1991) noted that the thickness of the anorthositic footwall was positively correlated with the thickness of the overlying chromitite, specifically for the Merensky Reef near Rustenburg (as shown in figure 12A), and inferred a causal link. Mungall et al. (2016) successfully modelled the major element compositions of the footwall anorthosite units as residues of partially melted footwall norite (Fig. 12B), induced by emplacement of ultramafic sills above them, which themselves become the hosts to the mineralized reefs. These models are consistent with the suggestion of Latypov et al. (2016) that the chromitite reefs are, in part, formed from Cr extracted from their footwalls as a consequence of partial melting, a variant on the model that was proposed by Nicholson and Mathez (1991) involving scavenging of chromium from the cumulate pile underlying the reefs by partial remelting induced by compaction-driven interstitial hydrous fluid migration upwards, but which they later rejected

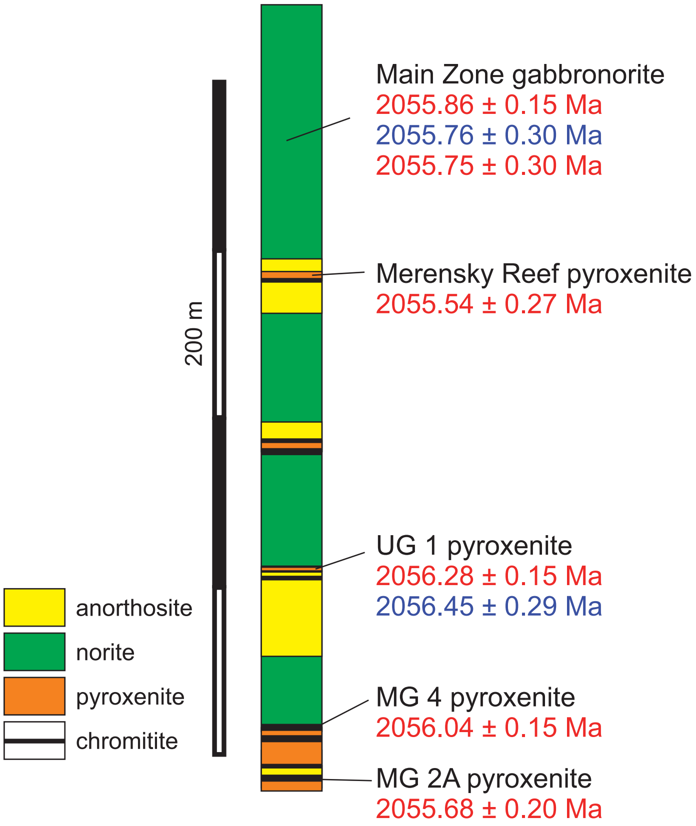

Figure 9. Simplified stratigraphy and summary of the U–Pb geochronological results of Mungall et al. (2016). Ages in red are from zircon separates, ages in blue are from baddeleyite grains.

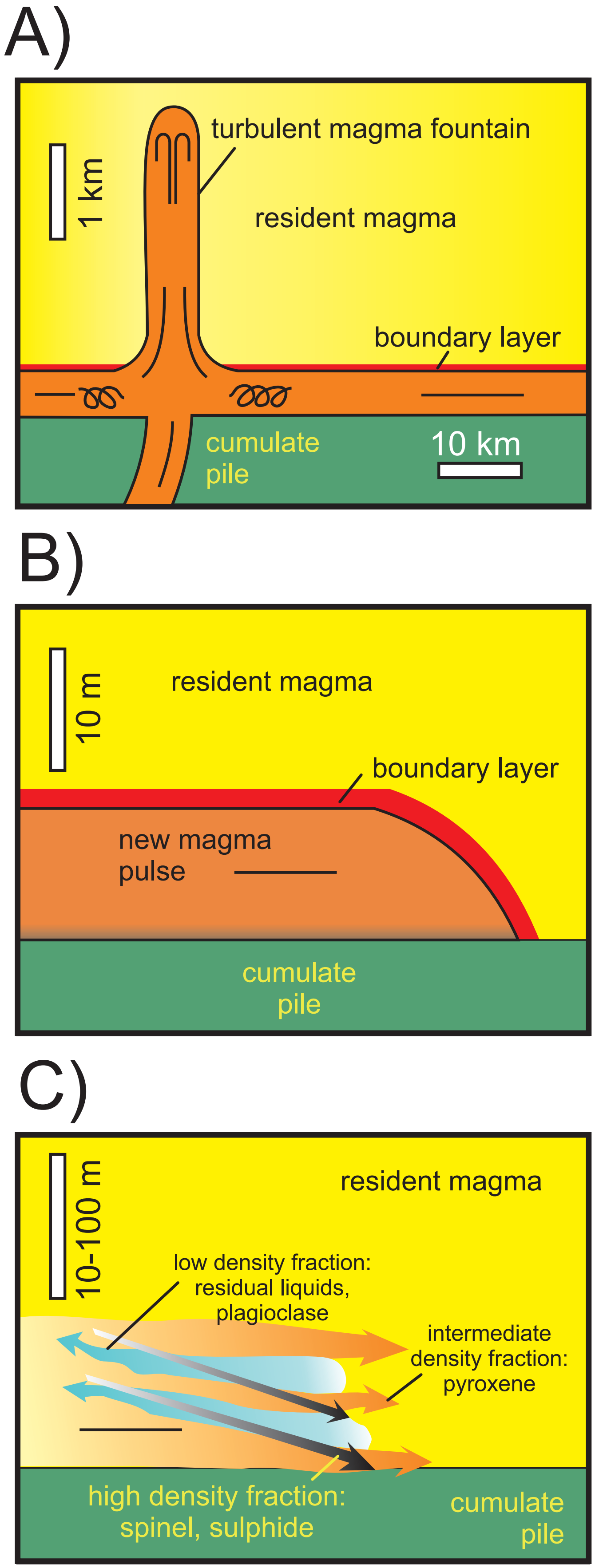

Figure 10. Schematic illustrations of proposed mechanisms for chromite+PGE sulphide-bearing reefs of the Bushveld Complex, with specific application to the Merensky Reef. In each diagram, the transient magma chamber floor is represented as the top of the cumulate pile. Note that the 'resident magma' above would also likely be a crystal-liquid suspension (e.g. Marsh 1996). Boundary layer zones occurring along the interfaces of new magma pulses and resident magmas represent sites of diffusive interaction and progressive compositional change. Black arrows indicate principal motion directions.

In A), Scoon and Teigler (1994) proposed magma introduction as a prominent fountain, followed by lateral settling of the hybrid magma across the floor, with the scale of the lateral flow being on the order of 0.5 km or more. The new magma is represented as turbulent throughout, as well as interacting with resident magma at the plume and along the boundary layer interface. The resident magma composition, and subsequently that of the magma flow, also changes with proximity to the influx plume. These ideas appear have been refined (Mitchell and Scoon 2007) to correspond with influxes with flow thicknesses on the order of metres, dominated by the pyroxenitic component, although this is not explicitly stated as such.

In B), Naldrett et al. (2009) proposed a comparable model in terms of flow geometry and boundary layer localized diffusion and mixing, omitting the magma fountain and the proximal/distal elements from their model, although they elsewhere espoused the concept of magma pluming and roof interaction to facilitate crustal contamination and resultant sulphide and spinel precipitation, which settle according to density to the flow base.

In C), Maier et al. (2013) proposed a variant wherein components are separated by hydrodynamic sorting (i.e. based on density and shape) during lateral flow, with flow scales on the order of tens to hundreds of metres. Experimental studies by Forien et al. (2015) demonstrated the practical application of such a process.

(Mondal and Mathez 2007) on the grounds of Cr budget inadequacies. Latypov et al. (2016) supplemented floor-derived chromium with chromite precipitated by magma mixing within the resident liquid column and have separately proposed pressure decrease during magma ascent from the upper mantle (e.g. Latypov et al. 2018b) as an additional mechanism for inducing chromite precipitation from the host melt, thereby relieving the pressure (so to speak) on the footwall as the sole source for chromium.

As alternatives to models where the modally variable suite is an internally differentiated entity, as described above, or where the anorthositic strata are induced by the intrusion of hot overlying magmas, Hunt et al. (2018) have suggested that the apparent cyclicity of the Merensky Reef specifically is an artifact of the introduction of at least five separate magma influxes, based primarily on existing geochemical indicators, supported by crystal size distribution analysis.

CONSTRAINTS ON MINERALIZATION MODELS

The magmatic models for chromium and PGE-bearing sulphide accumulation in Critical Zone reefs have been summarized in many recent publications (e.g. Naldrett et al. 2012; Maier et al. 2013; Latypov et al. 2016), and so will only be briefly listed here, rather than comprehensively analyzed.

Irvine (1975) proposed chromite-only precipitation by siliceous contamination of olivine or olivine-chromite crystallizing melts; sulphur-saturation driven by crustal contamination, inducing immiscible sulphide melt formation and subsequent metal scavenging, is also well established (e.g. Naldrett 1989). Irvine (1977) later cast doubt on his crustal contamination model, noting the stabilization of olivine by the coexisting alkali elements (K, Na), such that unless the contaminant was

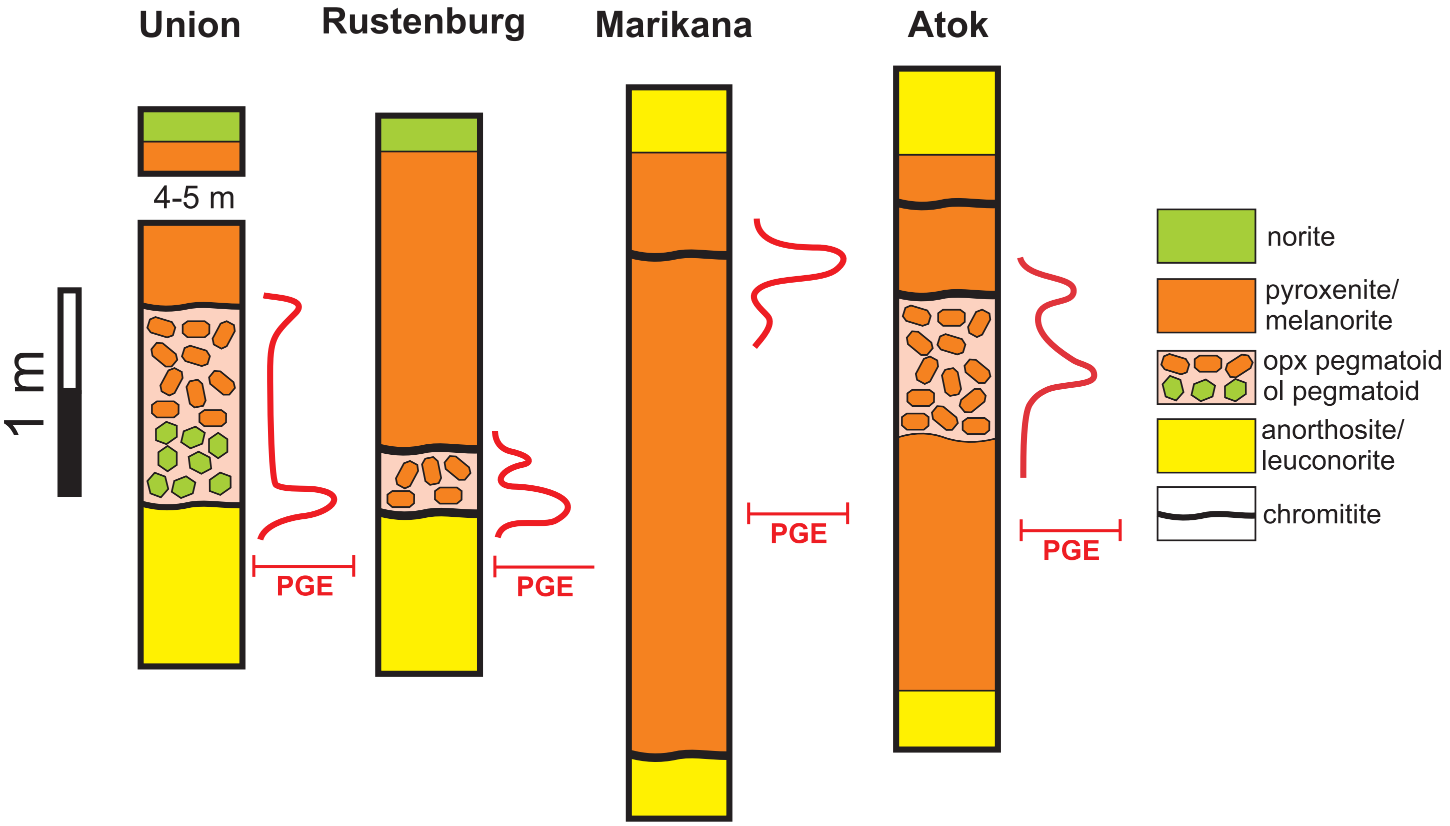

Figure 11. Summary of various Merensky Reef facies, modified after Campbell et al. (1983). The sections are presented from west to east, with Atok as the only representative of the Eastern Lobe of the Bushveld Igneous Complex (BIC). A case could be made for interpreting trends from Union to Marikana as proximal to distal facies changes. Qualitative PGE abundance profiles are indicated as red lines, showing the association of PGE with chromitite seams and pegmatoid rocks, generally.

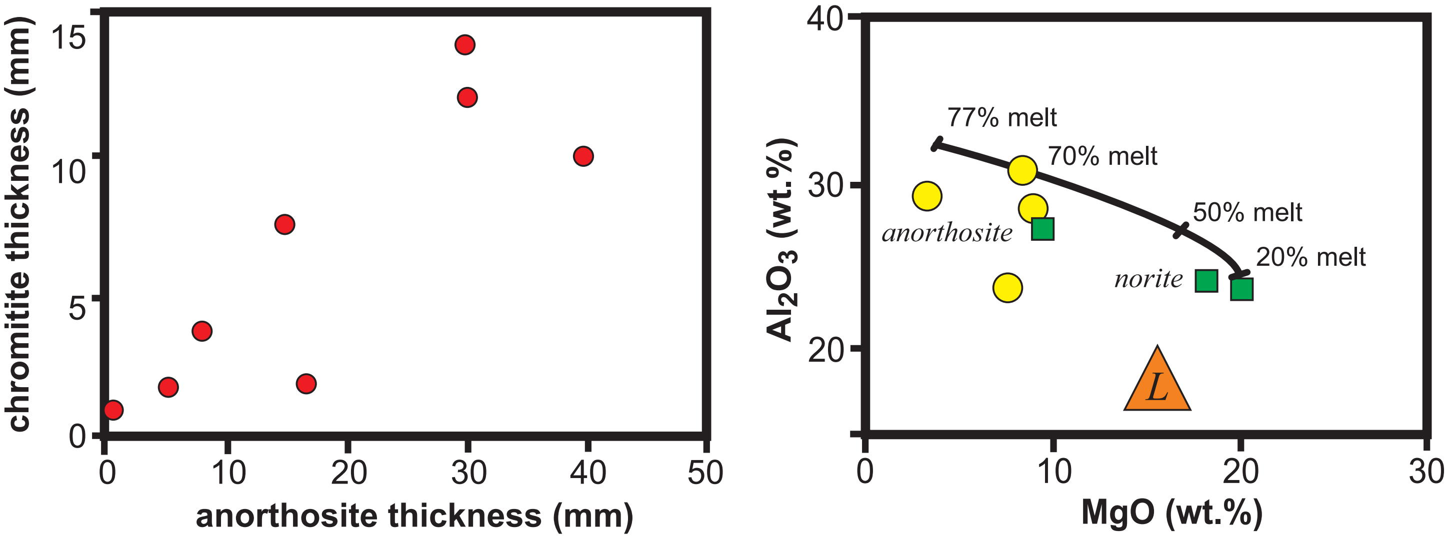

Figure 12. A) Correlated thicknesses of chromitite and corresponding underlying anorthosite from the Merensky Reef in the Rustenburg area, after Nicholson and Mathez (1991); B) Modelled partial melting of noritic host rocks (green squares) for the UG-2, consistent with production of residual anorthositic footwall as mixtures of partial melt residues (along the curve) and the liquid (L), after Mungall et al. (2016).

pure silica, the associated alkali elements would require extreme (> 50 wt.%) amounts of crustal contamination in order to pull the melt composition into the field of chromite-only crystallization. He proposed an alternative model of magma mixing instead, which avoided the problem of alkali stabilization and of requiring the introduction of an external component (the contaminant). This mixing model was also subsequently proposed as a mechanism for inducing sulphide precipitation (e.g. Naldrett and von Gruenewaldt 1989) during the same process, to account for the typical broad association of sulphide phases and chromitite. This process would thus allow for a new pulse of relatively primitive magma, mixing with the evolved residue of a previous pulse of the same or similar magma, to induce both chromite and sulphur saturation. However, recent reanalysis of this model by Li et al. (2001) and Cawthorn (2002) has demonstrated that the mixed magma resulting from such a process will not lie in the field of sulphur oversaturation. While this by no means rules out mixing of two dissimilar magmas as a mechanism, it does suggest that a simple replenishment model may not be appropriate for the production of coincident chromitite and (largely) sulphide-hosted PGE-bearing mineralized horizons.

Alternative mechanisms for generating either or both spinel and sulphide saturation have been proposed in order to account for features of mineralized reefs including, but not limited to:

- absence of cryptic, modal or whole-rock geochemical variation across immediate footwall and hangingwall rocks to chromitite or magnetitite reefs (e.g. Mondal and Mathez 2007), which offers no obvious evidence for mixing of dissimilar magmas;
- inconsistent relationship of pegmatoid bodies to mineralized reefs (such as shown in Fig. 8), which complicates the perception of mineralization models dependent on high water contents in melts;
- the ability to instigate mineral precipitation with comparable metal contents (e.g. Cr contents in chromite, V contents in magnetite, PGE contents in sulphide minerals), apparently simultaneously over large lateral distances across the intrusion.

These models include ephemeral pressure change, such as that proposed for Stillwater chromitite by Lipin (1993) and subsequently applied to the Bushveld Complex for chromitite and sulphide reef formation by Cawthorn (2005). Pressure increase may be derived by degassing of ascending magmas (Lipin 1993), and/or loading of new magmas onto an existing liquid-crystal pile (Cawthorn 2005). This process has the benefit of offering a mechanism for pervasive instantaneous pressure change, thereby shifting the phase boundaries for spinel relative to coexisting silicate minerals, and to be virtually untestable in terms of mineral chemical evidence, always an attractive feature for such models. The amount of pressure change suggested by Lipin (1993) for shallow crustal magmas is on the order of 0.25 kbar, which realistically would be undetectable in terms of mineral chemistry in slow-cooling magmatic systems. A problem with pressure change models is that there is no associated primary process that would include the introduction of radiogenic material coincident with the mineralization, such as that evident for the Bushveld chromitite layers specifically (Fig. 7). Phenomena like this, and the presence of associated pegmatoidal phases, would have to be attributed to later magmatic or post-magmatic processes not directly related to ore formation.

Other processes, such as inducing spinel oversaturation by magma oxidation, are similarly rather difficult to assess and have not been much tested directly, but have been proposed for other intrusions based on stable isotopic evidence for carbonate assimilation which has stimulated either chromite and sulphide saturation in the Uitkomst Complex (Gauert 2001) or magnetite oversaturation in the Panzhihua layered mafic intrusion (China) (Ganino et al. 2013). The concept of immiscible metal-rich liquids, proposed but discarded early on in evaluations of evolved Bushveld rocks (Reynolds 1985), has re-emerged in light of studies of thick Fe–Ti–V oxide deposits in China over the past decade or so (Zhou et al. 2013; Fischer et al. 2016; Nielsen et al. 2017).

Effectively in parallel to the pursuit of the various magmatic models, the role of aqueous magmatic fluids as agents of primary metal distribution has been proposed, mainly based on models developed from studies on the Stillwater Complex (U.S.A.) and then subsequently applied to Bushveld Critical Zone rocks (Nicholson and Mathez 1991; Willmore et al. 2000; Boudreau 2008; Chutas et al. 2012). Vapour-rich late magmatic environments may have played a significant role in the development of both chromite and sulphide ores, and pothole-related mineralization, if not pothole development. The specific mechanics of aqueous fluid movement through a compacting crystal–liquid mush has been favourably analyzed by Boudreau (2016) and critically perceived by Mungall (2015), for example. As with other high profile mineralization geological settings, such as Sudbury or the Witwatersrand Basin, it is with great trepidation and reluctance (what in Afrikaans, one of the languages of the Bushveld Complex, is idiomatically described as to *eet met long tande*, or to “eat with long teeth”) that the hot, dry, primary magmatic model is even slightly abandoned for a dip in the pool of late magmatic fluid petrogenesis. The fundamentals of the hydromagmatic models were established in the 1980s and 1990s, and continue to be refined subsequently, if not (yet) widely embraced.

NATURE AND EXTENT OF CONTAMINATION

One of the distinctive features of the Bushveld Complex is the relatively large and pervasive extent of crustal contamination, as revealed by the radiogenic isotopic compositions. The Sr isotope stratigraphy of the complex was established in the 1990s (Kruger 1994 and others), complemented by some common lead isotope work, but the last two decades have seen the application, at least locally, of Sm–Nd, Lu–Hf, Re–Os and other exotica. This review will refer the reader to a recent (Boudreau 2019) review of the state of the isotopic literature over this time. His review summarizes and attempts to reconcile the various efforts to effectively characterize the Rustenburg Layered Suite rocks and to rationalize the models devised to explain the isotopic evidence for mineral disequilibrium particularly evident near the interface between the Critical and Main Zones, within which the Merensky Reef is hosted. Proposed models range from mixing of cumulate mushes (Roelofse and Ashwal 2012) to magmatic fluid control (Chutas et al. 2012).

The trace element composition of the B1 and B2 magmas is consistent with extensive contamination of the former by upper continental crust, and the latter by lower continental crust (Arndt 2005; Barnes et al. 2010). This conclusion is also consistent with interpretations of oxygen isotopic compositions (Harris and Chaumba 2001; Harris et al. 2005), as well as Sm–Nd isotope systematics (Maier at al. 2000; Prevec et al. 2005), suggesting on the order of up to 30 to 40 wt.% crustal contamination for parts of the Bushveld, although lesser quantities (< 30 wt.%) of more ancient (3.5–3.1 Ga) crust have also been proposed as alternatives (Prevec et al. 2005; Roelofse and Ashwal 2012). This would also be consistent with the suggestion that an isotopically enriched source, such as specifically a metasomatized subcontinental lithospheric mantle (SCLM), interacting with a mantle plume, was the primary melt source, requiring lesser amounts of syn-emplacement crustal contamination subsequently (Barnes et al. 2010; Maier et al. 2018).

NATURE OF THE PLATREEF

The nature of the Rustenburg Layered Suite in the Northern Lobe has gained attention in the past two decades because of the economics of platinum during much of that time period. The initial mapping of the lobe (van der Merwe 1978), which remains robust, indicated that while the Main and Upper Zone correlative rocks were relatively well-developed, the extent of the Critical and Lower Zones was less clear (e.g. von Gruenewaldt et al. 1989; Yudovskaya et al. 2013b). Recent reviews offer a useful overview of the developments in Northern Lobe research as of about five years ago or so (Kinnaird and McDonald 2005 and accompanying papers; McDonald and Holwell 2011). The lobe has been distinguished by the presence of PGE–Cu–Ni-sulphide ores hosted in deposits that are distinctively different from the ‘normal’ Bushveld Critical Zone-hosted ores that have been the subject of the preceding discussion. Specifically, the ores to date are hosted in massive sulphide phases, with extensive interaction with a variety of footwall lithologies, and without the presence of associated laterally continuous chromitite layers, and the nature of the parent magma to the ores has been only tentatively correlated with the Critical Zone magma as characterized elsewhere. Consequently, the ore-hosting unit has been known as the Platreef, to signify this distinction of the Northern Lobe stratigraphy. The Platreef mineralization style is much more reminiscent of that of the Uitkomst Complex than of traditional Upper Critical Zone PGE ore deposits. Stable isotope (S, O) compositions are consistent with significant footwall-derived contributions to the Bushveld magma, but also may indicate both local and pre-emplacement contamination and sulphur saturation, as well as secondary fluid involvement (Sharman-Harris et al. 2005). More recent examination of Re–Os and S isotopes in sulphides specifically indicates that while the Lower Zone ultramafic rocks show evidence for local S, the overlying Platreef is dominated by magmatic mantle sulphur (Yudovskaya et al. 2017a). Due to the heterogeneous nature of the local footwall (which includes granite, banded iron formation, carbonate rocks and shale), the nature of the magmatic-hosted footwall-rich basal breccia displays significant lateral variation, further complicated by structural control on the footwall (Nex 2006). The apparent consensus at that time (in that compilation) was for a genetic model for the Platreef involving multiple injections of relatively ultramafic sills (Kinnaird 2005), and that this mineralization process preceded the emplacement of the overlying Main Zone (Holwell et al. 2005), contrasting with models based on the Western and Eastern Lobes as described earlier.

More recently, new sections have been discovered to the south of the studied sections that display much less disrupted magmatic stratigraphy (Yudovskaya et al. 2017b), and that can be more directly correlated with equivalent Upper Critical stratigraphy elsewhere. These sections have been distinguished from the Platreef by identifying it as “thick reef facies” and, to the south, as “Flatreef” (Grobler et al. 2018) based on regional changes (local flattening) of the stratigraphy as contrasted to that observed to the north. This has allowed for the identification of UG2- and Merensky Reef-equivalent stratigraphy in the Northern Lobe (Yudovskaya et al. 2017b; Grobler et al. 2018), albeit with much more extensive footwall-derived contamination and sulphide-mineralization styles that are consistent with the Platreef setting.

PROSPECTIVE RESEARCH DIRECTIONS

In addition to the recently enhanced research on previously relatively under-studied areas such as the Northern Lobe, and the application of micro-analytical and penetrative scanning technologies to well-contextualized ore-bearing layers (Godel et al. 2010 and references therein), recent international conferences and workshops have identified a variety of potentially constructive directions in which insight is required. These include experimental studies on Cr spinel stability, which remain relatively poorly constrained, in particular their dependence on factors such as pressure, oxygen fugacity, and water content of the magma. The mobility of the platinum group metals in high temperature systems remains relatively poorly understood, whether this relates to their preference for alloys versus sulphide complexes during magmatic crystallization, or the likelihood of formation of and mobility in metal–chloride complexes in such environments. On a more fundamental scale, the application of material sciences theory relating to the behaviour of crystal-liquid slurry systems, for application to so-called crystal mushes, is poorly understood within the geological community, particularly those involved in layered intrusion study. The distinction between the behaviour of incompressible liquids and crystal–liquid mush systems is perceived to be crucial in our better understanding of layered intrusion evolution. Complementing this would be the application and construction of relevant physical and numerical models to examine magmatic processes, such as those developed and applied by Campbell and others in the 1970s (see Campbell 1996 and references therein) to such great effect.

CONCLUSIONS

Despite over a century of mining and research study, the Bushveld Complex, South Africa, remains a hotbed of innovation and re-examination. In the two decades since the most substantive review was published (Eales and Cawthorn 1996), the perception of the Bushveld Complex has gone from a suite of discrete intrusions whose behaviour was governed by basic principles of igneous petrology based on the principles developed by Bowen and applied by Wager and others, involving the actions of relatively predictable *in situ* processes in a closed system controlled by density contrasts and phase relationships, fed by basaltic sills, to a situation where virtually none of these precepts have escaped serious re-evaluation. The current paradigms involve boundary layer interactions in a relatively open system of a single, large intrusive complex, probably linked at depth to other laterally equivalent contemporaneous satellite bodies. Fundamental principles of the nature of magma emplacement and the formation of modal layering and stratiform ore deposits have been constrained by detailed isotopic, mineral chemical, geochronological and micropetrological studies, linked to phase theory. The nature of the parental magmas has shifted from the basaltic sills mapped in the floor through boninitic to komatiitic compositions, and the formerly closed system based on a relatively complete differentiated sequence, has been replaced by an open system where the existing complex is perceived as the residue of much larger volumes of primary magma. The role of variations in pressure, oxygen fugacity and water, as well as liquid immiscibility, as controls of primary magmatic evolution, have been re-introduced to the debate. The result is that much more is known about the world's largest known layered intrusion, and probably much less agreed upon, than ever before.

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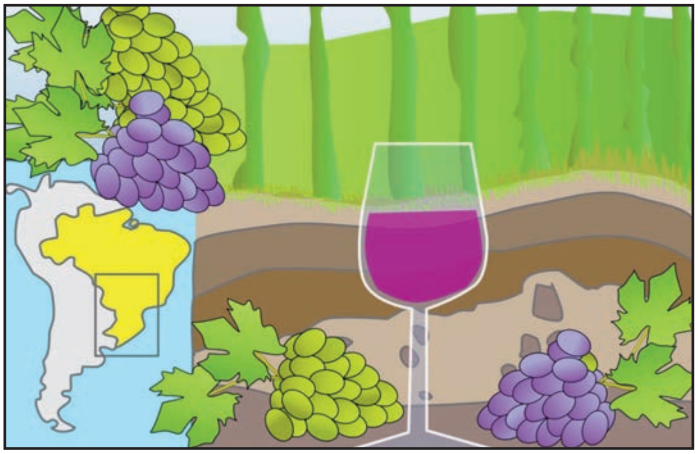

Geology and Wine 15. Producing Wine at Altitude: The *Terroir* of São Joaquim, Brazil

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SUMMARY

The municipality of São Joaquim, located in the Planalto Catarinense viticultural region, is the coldest wine-growing region of Brazil, and contains the highest-altitude vineyards in the country. These vineyards were established within the last 20 years, so this is a young and still-developing viticultural region. Information on the *terroir* of São Joaquim is needed in order to identify potential vineyard sites and to help improve the viticulture in the region. This work aims to characterize the terroir of São Joaquim, where wines are produced from grapes cultivated above 900 m of altitude, through a description and analysis of meteorological, physiographic, pedological, geological and viticultural factors. With respect to these factors, the São Joaquim region presents the following characteristics:

1 It has an annual mean temperature of 13ºC, annual mean precipitation of 1680 mm/year and an annual mean solar radiation of 1832 hours/year.
2 It has altitudes between 715–1638 m and generally steep slopes, 43% of the slopes have declivities between 20–45% and show no preferred orientation.
3 It has both deep (> 150 cm) and shallow (< 100 cm) soils with clayey texture, an average pH (water) between 4.68–5.52 and an average soil organic matter (SOM) content of 6%.
4 It is underlain by two units of volcanic rocks. These are a mafic unit (50.53–55.09 wt.% SiO_2) and a felsic unit (66.58–70.12 wt.% SiO_2). The mafic unit tends to consist of thicker flows than the felsic unit and is characterized by generally steeper slopes.
5 There is a correlation between the geological unit and the soil types, in which thicker inceptsols are preferentially developed on the mafic volcanic rocks and thinner entisols are preferentially developed on the felsic volcanic rocks.
6 Currently, the region produces more than 27 grape varieties planted mostly on the Paulsen 1103 rootstock. The existing vineyards are mostly underlain by the mafic volcanic unit in areas of steep north-facing slopes.

This preliminary study suggests that there are correlations between the bedrock, the soils that they give rise to and the declivities of the slopes. Knowledge of these relationships should assist in the evaluation and planning of future grape and wine production.

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RÉSUMÉ

La commune de São Joaquim, située dans la région viticole de Planalto Catarinense, est la région viticole la plus froide du Brésil et abrite les vignobles les plus élevés du pays. Ces vignobles ont été établis au cours des 20 dernières années; c'est donc une région viticole jeune et en développement. Des informations sur le terroir de São Joaquim sont requises pour identifier les sites viticoles potentiels et contribuer à l'amélioration de la viticulture dans la région. Ce travail vise à caractériser le terroir de São Joaquim, où les vins sont produits à partir de raisins cultivés à plus de 900 m d'altitude, au moyen d'une description et d'une analyse des facteurs météorologiques, physiographiques, pédologiques, géologiques et viticoles. En ce qui concerne ces facteurs, la région de São Joaquim présente les caractéristiques suivantes:

1 Sa température moyenne annuelle est de 13ºC, ses précipitations moyennes annuelles de1680 mm/an et son rayonnement solaire moyen annuel de 1832 heures/an.
2 Son altitude est comprise entre 715 et 1638 m et ses pentes généralement abruptes. 43% des pentes ont des déclivités comprises entre 20 et 45% et ne présentent aucune orientation préférentielle.
3 Ses sols sont profonds (> 150 cm) et peu profonds (<100 cm) de texture argileuse, avec un pH moyen (eau) compris entre 4,68 et 5,52 et une teneur moyenne en matière organique du sol (MOS) de 6%.
4 Elle repose sur deux unités de roches volcaniques. Il s'agit d'une unité mafique (50,53 à 55,09 % en poids de SiO_2) et d'une unité felsique (66,58 à 70,12 % en poids de SiO_2). L'unité mafique est généralement constituée de coulées plus épaisses que l'unité felsique et se caractérise par des pentes généralement plus raides.
5 Il existe une corrélation entre unité géologique et types de sol, dans lesquels des inceptsols plus épais sont préférentiellement développés sur les roches volcaniques mafiques et des entisols plus minces sont préférentiellement développés sur les roches volcaniques felsiques.
6 La région produit actuellement plus de 27 cépages principalement plantés sur le porte-greffe Paulsen 1103. Les vignobles existants reposent principalement sur l'unité volcanique mafique dans des zones de pentes abruptes exposées au nord.

Cette étude préliminaire suggère qu'il existe des corrélations entre la lithologie, les sols qu'elles engendrent et les déclivités des pentes. La connaissance de ces relations devrait faciliter l'évaluation et la planification de la production future de raisins et de vin.

INTRODUCTION

Altitude has a significant influence in viticulture. Every 100 m increase in altitude produces a decrease of 0.6ºC in the mean temperature, which can make regions that are close to one another, but at distinct altitudes, very different in terms of their viticultural suitability. The highest vineyard in the world is located in Argentina (Salta, 3100 m), followed by vineyards in Chile (Elqui, 2500 m), China (Yunnan, 2300–2600 m), the USA (Colorado, 1950 m), Lebanon (1700 m), Spain (Tenerife, 1650 m), Mexico (1500–1700 m) and Brazil (Santa Catarina, 1427 m) (Easton 2016). In Brazil, these high-altitude vineyards are located in the Planalto Catarinense viticultural region, in the State of Santa Catarina (Fig. 1), characterized by high relative altitude, strong relief and soils of volcanic origin. In this region, according to Rosier (2003), the altitude generates climatic conditions that displace the entire productive cycle of the vine. In most viticultural regions of Brazil, grapes sprout in early September and harvested in February, but due to the unique climatic condition of the Planalto Catarinese, bud break occurs in mid-October and maturation occurs in mid-April, when precipitation is less common and the temperatures are milder, causing the vines to prioritize fruit development rather than vegetative growth (Rosier 2003).

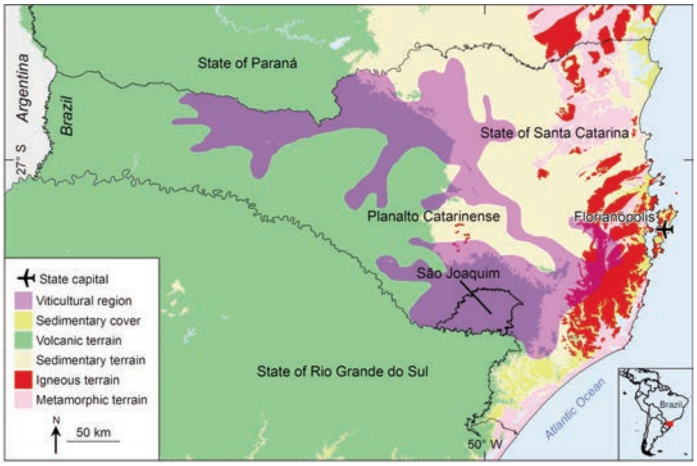

Figure 1. Location map of the Planalto Catarinense viticultural region and the municipality of São Joaquim, State of Santa Catarina, Brazil. Geological data from CPRM (2015).

São Joaquim is the municipality with the largest number of properties dedicated to viticulture in the State of Santa Catarina and the number of vineyards has significantly increased in the last few years (from 181 vineyards in 2009 to 268 in 2013, according to Vianna et al. 2016). As shown by the data collected from the "2013 vineyards of altitude geo-referencing of Santa Catarina" completed by Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI), the municipality of São Joaquim contains 21 properties comprising 268 vineyards that occupy a total area of 168.13 ha (Vianna et al. 2016).

São Joaquim includes the 8th highest vineyard in the world (Vinícola Hiragami, 1427 m) (Fig. 2) and is the best example of high-altitude viticulture in Brazil. The most common cultivated varieties are Cabernet Sauvignon, Merlot, Sauvignon Blanc, Pinot Noir, Chardonnay, Sangiovese, Touriga Nacional, Montepulciano and Cabernet Franc. The aim of this work is to evaluate this peculiar Brazilian terroir, where wines are produced from grapes cultivated at altitudes higher than 900 m, based on the principles outlined by Haynes (1999), through a description and analysis of meteorological, physiographic, pedological, geological and viticultural factors.

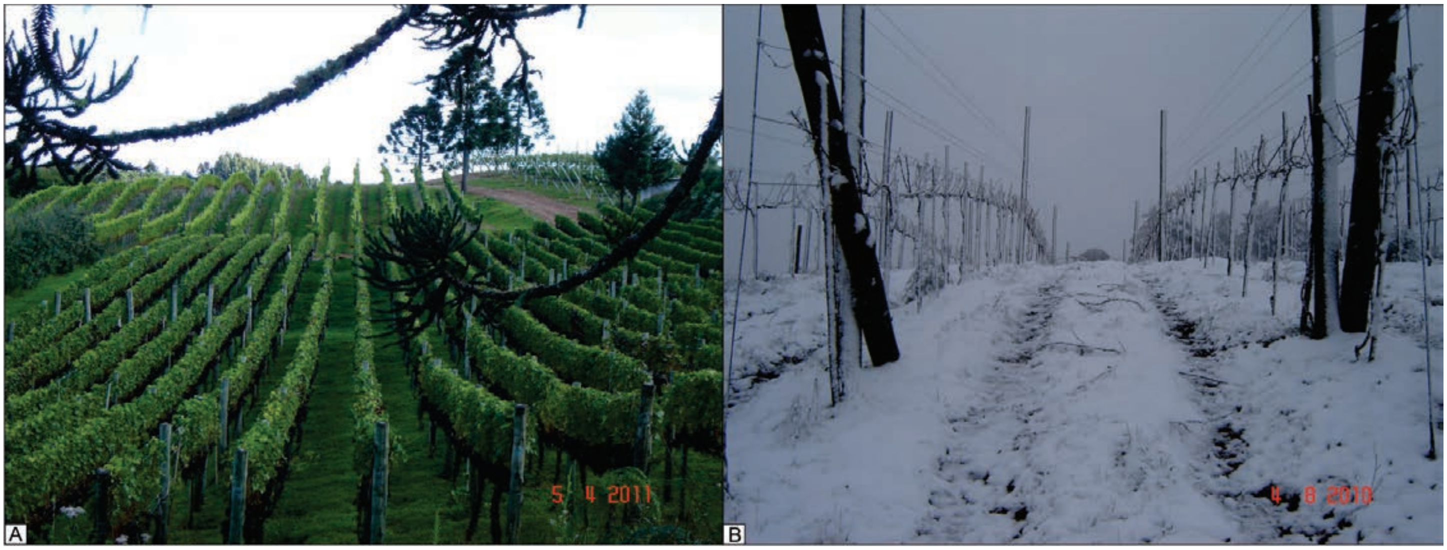

Figure 2. The 8th highest vineyard in the world (Vinícola Hiragami, at 1427 m): (A) during the harvest and (B) during the winter. Photograph provided by Celito Soldá.

REGIONAL GEOLOGY

The Paraná-Etendeka Magmatic Province (Fig. 3) was formed by a large volcanic event in the Early Cretaceous that lasted approximately 3 Ma (~134.5–131.5 Ma; Janasi et al. 2011), and which preceded the rifting of Gondwana and the opening of the Atlantic Ocean. Lava flows and shallow intrusive bodies form a sequence of magmatic rocks composed of continental tholeiitic basalt (90%), tholeiitic andesite (7%) and subordinate dacite, rhyodacite and rhyolite (Bellieni et al. 1986). These rocks are now found in the southern and central-western regions of Brazil (termed the Serra Geral Group), in south-eastern Paraguay, in northern Argentina, in eastern Uruguay and also in Namibia, which was adjacent to South America at ca. 134 Ma.

The rocks of the Serra Geral Group (Rossetti et al. 2018) have an estimated volume of at least 600,000 km³ of which about 75% is represented by extrusive rocks and the remainder by related shallow intrusive rocks, in the form of sills and dikes. Collectively, rocks of the Serra Geral Group cover an area of approximately 917,000 km² (Frank et al. 2009).

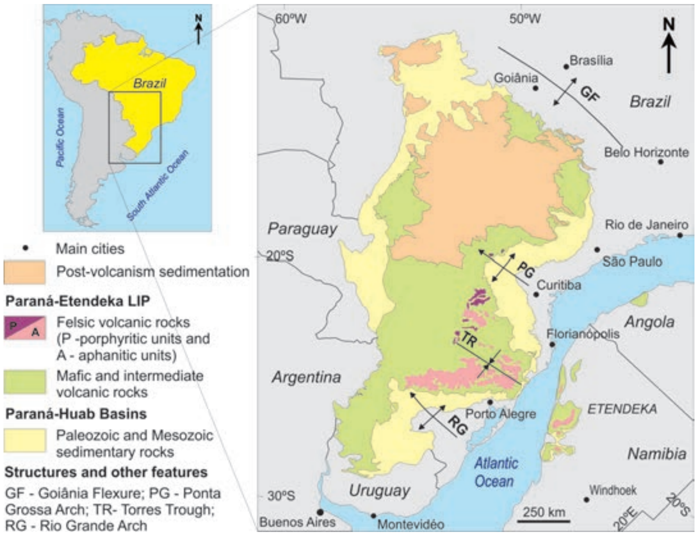

Figure 3. Geological map of the Early Cretaceous Parana-Etendeka Magmatic Province in South America and Africa. Modified from Licht (2018).

METHODOLOGY

Our integrated study of the terroir of São Joaquim used meteorological, physiographic, pedological, geological and viticultural data and a geographic information system (GIS) to analyze and describe these factors. The meteorological data were obtained from the São Joaquim meteorological station (at latitude 28°18'00"S, longitude 49°55'48"W, elevation 1415 m), sourced from the Brazilian Instituto Nacional de Meteorologia (INMET 2016). The mean monthly and annual values for maximum temperature (ºC), mean temperature (ºC), minimum temperature (ºC), precipitation (mm) and solar radiation (hours) were calculated from these data. The meteorological maps were obtained from the Climatological Atlas of the State of Santa Catarina (Pandolfo et al. 2002).

The physiographic data were obtained from the Geomorphological Map presented in the Atlas of Santa Catarina (Santa Catarina 1986) and from the digital elevation model (DEM) of the municipality of São Joaquim, sourced from the Aerophotogrammetric Survey of the State of Santa Catarina (SDS 2010). The DEM was imported into ArcGIS® software (Release 10), for analysis. The altitudes were classified in intervals of 100 m. The steepness (declivity) of the slopes was calculated in percentage (%) using the *Slope tool* and their orientation was calculated using the *Aspect tool*.

Samples of soil were collected, along with the bedrock underlying the soil, to obtain pedological and geological data from the same sites. The pedological data were obtained from Potter et al. (2004) who published the map of the Soils of the State of Santa Catarina. The granulometric composition of the soil (sand, silt and clay proportions), pH (water) and soil organic matter content (SOM = 1.724*total organic carbon) were obtained using the methods in EMBRAPA (1997) and

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Tedesco et al. (1995). The geological data were obtained from the Geological Map of the State of Santa Catarina (DPNM 1986), and from Besser (2017), who presents a detailed geological map from São Joaquim region. The geochemical analyses (13 samples of mafic volcanic rocks and 29 samples of felsic volcanic rocks), were performed by X-ray fluorescence in two laboratories (UNESP-Rio Claro and LAMIR-UFPR). Major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5), were analyzed from glass pellets and are expressed in weight %. Trace elements (Cr, Ni, Ba, Rb, Sr, Zr, Y, Nb, Cu, Zn, Co and V), were analyzed from pressed pellets and are expressed in ppm.

The viticultural data were obtained from the "2013 vineyards of altitude geo-referencing of Santa Catarina" (EPAGRI 2013). In addition to these numerical data, bibliographic research of the other factors that might contribute to the terroir of São Joaquim was completed.

RESULTS

Meteorology

São Joaquim is the coldest Brazilian viticultural region, with an annual mean temperature of 13ºC (Table 1). The highest temperatures are in the summer (December–February), when the maximum mean temperature is between 22–23ºC and the lowest temperatures are in the winter (June–August), where the minimum mean temperature is between 6–7ºC. In the spring (September–November) mean temperatures range from 12–15ºC and in the autumn (March–May) from 11–16ºC. As shown in figures 4A, B and C, the observed temperatures all tend to be lower towards the northeast part of the municipality, where the altitudes are higher.

Precipitation is evenly distributed throughout the year, with a mean annual amount of 1680 mm/year (maximum of 175 mm in September and minimum of 92 mm in April) (Table 1). There is a variation in the amount of precipitation during the seasons of the year, with the highest rainfall in the summer (474 mm) and the lowest rainfall in the autumn (331 mm). As shown in Figure 5A, rainfall tends to be greatest towards the southeast part of the municipality.

The region receives abundant solar radiation, with a mean annual amount of 1832 hours/year (maximum of 173 hours in November and minimum of 128 hours in June). There is a small variation in the amount of solar radiation received during the seasons of the year: the highest values are in the summer (476 hours) and the lowest in the winter (417 hours). As shown in Figure 5B, the annual solar radiation received tends to be greater towards the western part of the municipality.

According to the Köppen (1936) criteria, Alvares et al. (2013) classified the climatic type of São Joaquim as type Cfb - Humid subtropical (C), Oceanic climate, without dry season (f) with temperate summer (b).

Physiography

The municipality is divided into two geomorphological units (Fig. 6A). The Iguaçu River/Uruguay River Dissected Plateau is characterized by deep valleys embedded in plateaus. The Campos Gerais Plateau is characterized by isolated high-relief blocks situated topographically above the surrounding areas (Santa Catarina 1991) that, in the municipality of São Joaquim, coincides with the area of the felsic volcanic unit, called the São Joaquim Plateau (Besser et al. 2015).

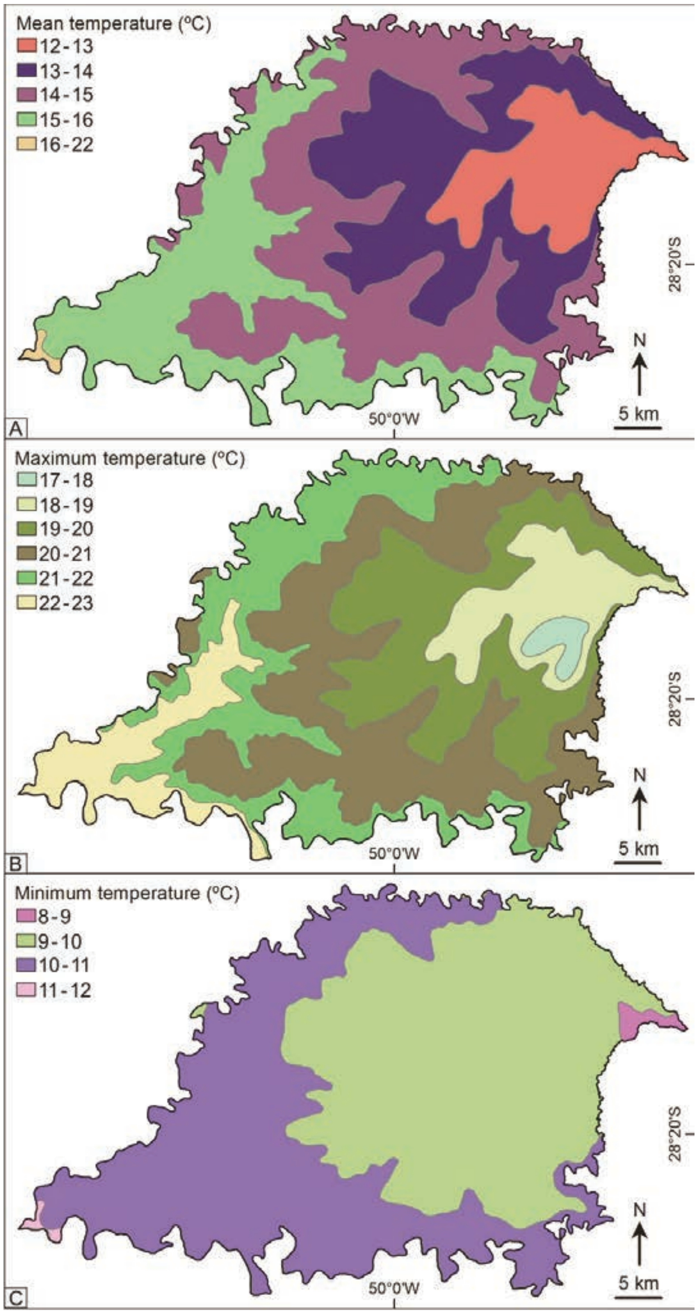

Figure 4. Meteorological maps of the municipality of São Joaquim: (A) annual mean temperature, (B) annual maximum temperature and (C) annual minimum temperature. Modified from Pandolfo et al. (2002).

São Joaquim is the highest Brazilian viticultural region, with altitudes ranging from 715 m in the southwest portion to 1638 m in the northeast portion of the municipality (Fig. 6B, Table 2). Slopes within the municipality tend to be steep, with most slopes (43% of the total) having declivities between 20–45% (Fig. 6C, Table 3) and showing no preferred orientation (Fig. 6D, Table 4).

Table 1. Historical meteorological data for temperature (ºC), precipitation (mm) and solar radiation (h) in the municipality of Sao Joaquim (1961–2015).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean	Annual amount
Mean maximum temperature (°C)	23	23	22	19	16	15	15	17	17	19	21	22	19	-
Mean temperature (°C)	17	17	16	14	11	10	10	11	12	13	15	16	13	-
Mean minimum temperature (°C)	13	13	12	10	8	6	6	7	8	9	10	12	10	-
Precipitation (mm)	168	170	136	92	104	119	140	145	175	164	132	136	140	1680
Solar radiation (h)	164	143	164	157	151	128	146	144	141	154	173	169	153	1832

*Data from INMET (2016).

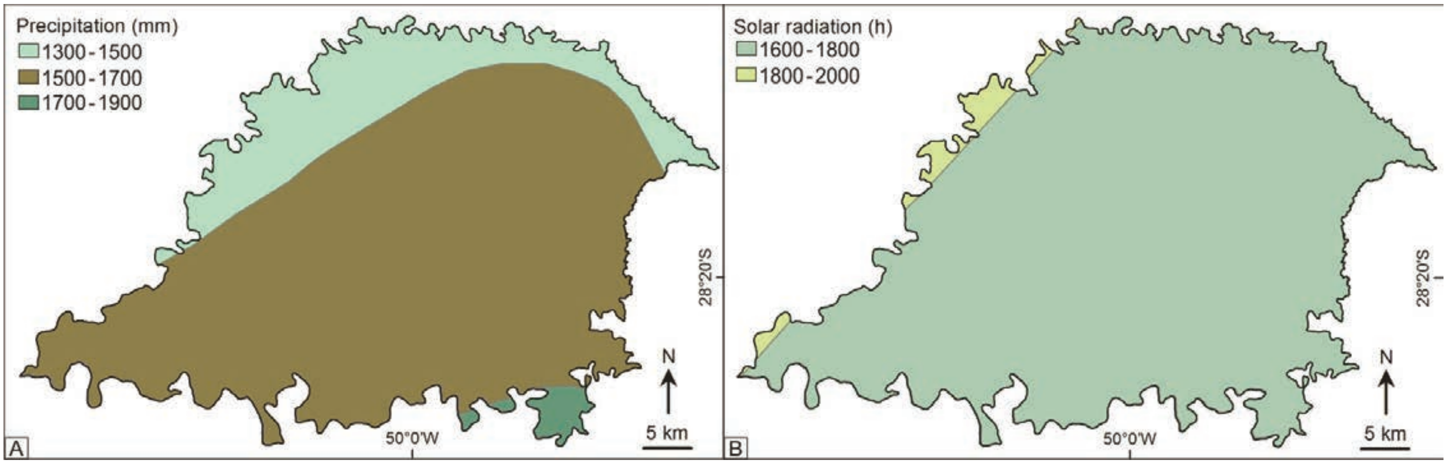

Figure 5. Meteorological maps of the municipality of São Joaquim: (A) annual mean amount of precipitation (mm) and (B) annual mean amount of solar radiation (h). Modified from Pandolfo et al. (2002).

Pedology

There are two types of soils, according to Potter et al. (2004) that predominate in the municipality of São Joaquim (Fig. 7A): *Cambissolos*, which are inceptsols, humic and haplic, that are 60 to 150 cm thick, and have a clayey to very clayey texture, and *Neossolos Litólicos,* which are entisols that are < 60 cm thick and have a clayey texture (Fig. 7A). Inceptisols are defined as soils of relatively new origin and are characterized by having only the weakest appearance of horizons, or layers, produced by soil-forming factors (e.g. Weil and Brady 2017, p. 99–100), and entisols are defined as soils defined by the absence or near absence of horizons (layers) that clearly reflect soil-forming processes (e.g. Weil and Brady 2017, p. 96–99). Representative soil profiles of the inceptsols and entisols from the region are listed in Table 5 and illustrated in Figures 8 and 9.

Geology

The geology of the municipality of São Joaquim is largely defined by the volcanic rocks of the Serra Geral Group, in which the mafic lava flows are overlain by the felsic flows (Fig. 7B). The mafic volcanic unit (50.53–55.09 wt.% SiO_2) occupies most parts of the region and is classified as Vale do Sol Formation at the base and Esmeralda Formation at the top. The lower flows are formed by low-Ti (~1.75 wt.%) and low Sr/Y (< 6.5) basaltic andesites that form thick rubbly pahoehoe flows. The upper flows are formed by low-Ti (~1.34–1.55 wt%) and high Sr/Y (> 7.5) pahoehoe flows that are typically thinner than the lower sequence (Besser et al. 2018). In addition, there are lava flows and some shallow sills of basaltic composition that have high Ti contents (> 3.5 wt.%), referred to as the Urubici magma type, according to Peate et al. (1992).

The felsic volcanic unit (66.58–70.12 wt.% SiO_2) is composed of at least eight tabular and lobate lava flows with total thickness of 150 m, occupying an approximate area of 270 km^2, with an estimated volume of 27 km^3. They are classified as low-Ti (0.86–1.08 wt.%) dacites with subordinate rhyolites, and are assigned to the Palmas Formation (Besser et al. 2018). Table 6 (major elements) and Table 7 (trace elements) give the average composition of the volcanic units in the municipality of São Joaquim, based on the samples collected in this study.

Viticulture

In the early 1990s, researchers from EPAGRI tested the adaptation of *Vitis vinifera* cultivars in several regions of the State of Santa Catarina, but the results were discouraging. However, the 1998 harvest from the Planalto Catarinense vineyards, such

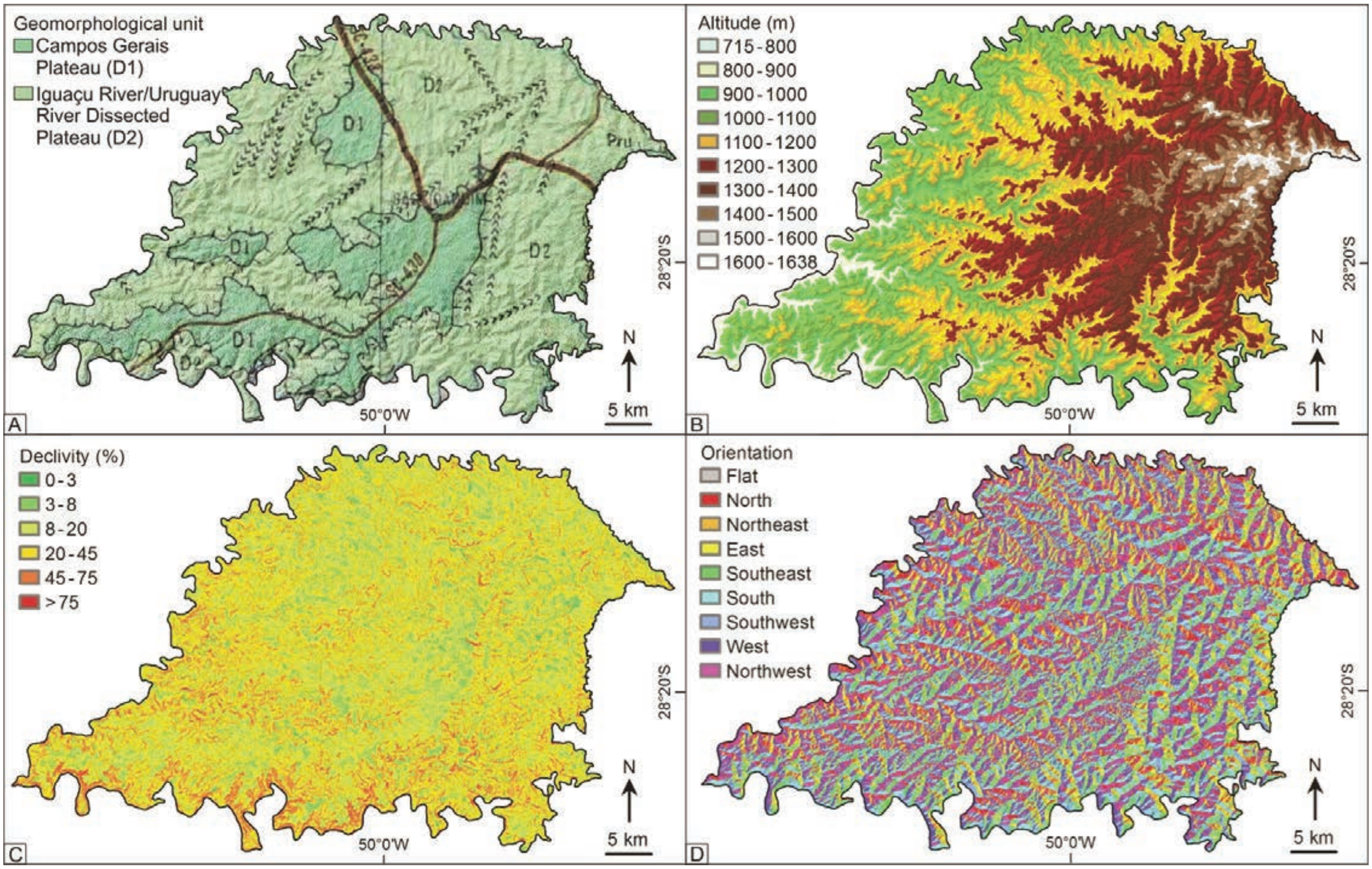

Figure 6. Physiographic maps of the municipality of São Joaquim: (A) geomorphological units, (B) altitude (m) in intervals of 100 m, (C) declivity (%) and (D) general orientation of the slopes. Modified from Santa Catarina (1986) and SDS (2010).

Table 2. Altitude data for the municipality of São Joaquim, classified in intervals of 100 m, with the area occupied by each interval expressed in km^2 and %.

Altitude (m)	Area (km^2)	Area (%)
715 - 800	13	1
800 - 900	72	4
900 - 1000	192	10
1000 -1100	377	20
1100 - 1200	470	25
1200 - 1300	375	20
1300 - 1400	248	13
1400 - 1500	116	6
1500 - 1600	24	1
1600 - 1638	1.06	~0
Total	1887	100

*Data from SDS (2010).

Table 3. Declivity data for slopes in the municipality of São Joaquim, classified in classes of percentage, with the area occupied by each class expressed in km^2 and %.

Declivity	Area (km^2)	Area (%)
0 - 3%	72	4
3 - 8%	214	11
8 - 20%	524	28
20 - 45%	813	43
45 - 75%	246	13
> 75%	18	1
Total	1887	100

*Data from SDS (2010).

as those of São Joaquim, produced sweet and balanced grapes (AL Notícias 2007). In 2000, EPAGRI started the "Technological Development for Vitiviniculture in the Planalto Serrano Project", to evaluate the adaptation of *Vitis vinifera* cultivars in the Serra Catarinense (BRDE 2005). A few years later, in November 2005, the "Catarinense Association of Producers of Fine Wines of Altitude" (Associação Catarinense dos Produtores de Vinhos Finos de Altitude - ACAVITIS) was founded. The organization is now known as "Wine of Altitude - Associated Producers of Santa Catarina" (Vinho de Altitude - Produtores Associados de Santa Catarina). This initiative consolidated the "Santa Catarina Fine Wine Program" in the State of Santa Catarina, and new projects were carried out in the municipality of São Joaquim, such as the Quinta da Neve and

Table 4. Orientation data for slopes in the municipality of São Joaquim, classified in classes of exposure direction (N, NE, E, SE, S, SW, W, NW and Flat), with the area occupied by each class expressed in km^2 and %.

Orientation	Area (km^2)	Area (%)
North	257	14
Northeast	215	11
East	200	11
Southeast	224	12
South	244	13
Southwest	229	12
West	247	13
Northwest	271	14
Flat	0.16	~0
Total	1887	100

*Data from SDS (2010).

the Villa Francioni (Protas and Camargo 2011). Currently, these are two major wineries of the region.

The main grape varieties grown in São Joaquim are Cabernet Sauvignon, Merlot, Sauvignon Blanc, Pinot Noir, Chardonnay, Sangiovese, Touriga Nacional, Montepulciano and Cabernet Franc, totalling over 422,000 vines (individual plants). These represent 91% of all vines and 90% of the total vineyard area in the region (Table 8 and Fig. 10). Other varieties cultivated in São Joaquim are Alicante Bouschet, Longanese, Molinara, Raboso, Rondinella, Incrocio Manzoni, Moscato Giallo, Nebbiolo, Pignolo, Aglianico, Malvasia, Rebo, Ribolla Gialla, Grechetto, Marselan, Refosco dal Peduncolo Rosso, Gewürztraminer, Petit Verdot, Tempranillo, Malbec, Moscatel, Nero d'Avola, Pinot Nero, Teroldego, Syrah, Moscato Bianco and Vermentino (EPAGRI 2013).

The most used rootstock in the south of Brazil since the 1990s (Camargo et al. 2011), and also in São Joaquim, is the Paulsen 1103, due to its lower productivity (Brighenti et al. 2011) and resistance to fungariosis. The vines are planted mostly in the vertical shoot positioning (VSP) system with spacing between the plants of 1.27 m (minimum of 0.7 m, maximum of 2.5 m), and spacing between the rows of 2.97 m (minimum of 1.2 m, maximum of 4.0 m) (EPAGRI 2013).

DISCUSSION

Meteorological Data

Temperature

According to Tonietto and Mandelli (2003), from the end of winter to early spring, a temperature of 10ºC is considered the general minimum for bud break and vegetative development of the plant. Between late spring and early summer, temperatures equal to or above 18ºC are the most suitable. In the summer, the highest photosynthetic activity is obtained at temperatures between 20–25ºC.

The mean temperature in São Joaquim, during the end of the winter and early spring (August–September), is between 11–12ºC, which allows the bud break and vegetative development of the vine. Temperatures during late spring to early summer (November–December) are between 15–16ºC and during the summer (December–February) they are between 16–17ºC. This lower summer temperature is the key climatic factor differentiating the region from other parts of Brazil, and it is what makes the vine to delay its vegetative growth and focus on fruit production, leading to a more complete maturation compared with other regions of Brazil.

Precipitation

The pluviometric indices (rainfall) of the best wine-producing regions in the world range between 300 and 1000 mm/year (van Leeuwen 2010). Compared to these regions, the annual precipitation in São Joaquim is greater (average of 1680 mm/year). From September to April (the growing season), the mean amount of precipitation is 997 mm. September is the wettest month (175 mm) and April is the driest month (92 mm). The fact that the harvest of some grape varieties in São Joaquim can occur in April, when the rainfall is the lowest, reduces the occurrence of fungal diseases.

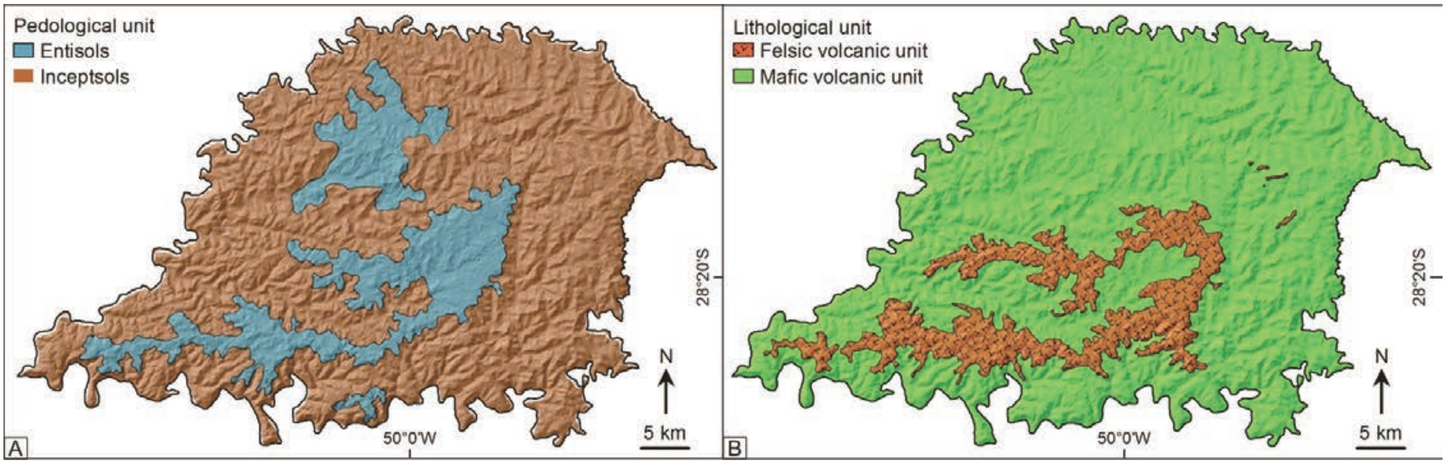

Figure 7. (A) Soil map of the municipality of São Joaquim, modified from Potter et al. (2004), and (B) lithological map of São Joaquim, modified from DNPM (1986) and Besser (2017).

Table 5. Pedological data of two representative soil profiles analyzed for chemical and physical properties in the municipality of São Joaquim: inceptsols (sample SJE-004) and entisols (sample SJE-006).

Sample	SJE 004 A1	SJE 004 A2	SJE 004 A3	SJE 004 AB	SJE 004 BA	SJE 004 B	SJE 006 A1	SJE 006 A2	SJE 006 A3	SJE 006 Cr
Soil type	Inceptsols						Entisols			
Depth (cm)	0 - 5	5 - 12	12 - 20	20 - 28	28 - 50	> 50	0 - 5	5 - 12	12 - 21	21 - 37
pH (water)	5.49	5.33	5.17	5.22	5.28	5.38	4.37	4.83	5.00	4.99
P^{-3} (ppm)	1.26	0.45	0.25	0.24	0.26	0.37	0.41	0.21	0.08	0.14
K^{+1} (ppm)	154	48	37	26	30	21	13	6	4	4
Ca^{+2} (ppm)	741	42	4	0	0	6	0	0	0	0
Mg^{+2} (ppm)	707	238	123	83	77	75	89	34	26	22
Al^{+3} (ppm)	63	246	310	288	308	250	470	511	477	533
SOM[1] (%)	11	8	7	5	4	2	7	6	5	3
Sand (%)	19	19	19	18	17	14	22	19	15	20
Silt (%)	36	33	32	26	25	30	32	26	27	27
Clay (%)	45	49	49	57	58	57	47	55	58	53
Silt/Clay	0.81	0.67	0.67	0.45	0.42	0.52	0.68	0.46	0.46	0.50
Textural Class	Clay						Clay			

[1]SOM = soil organic matter

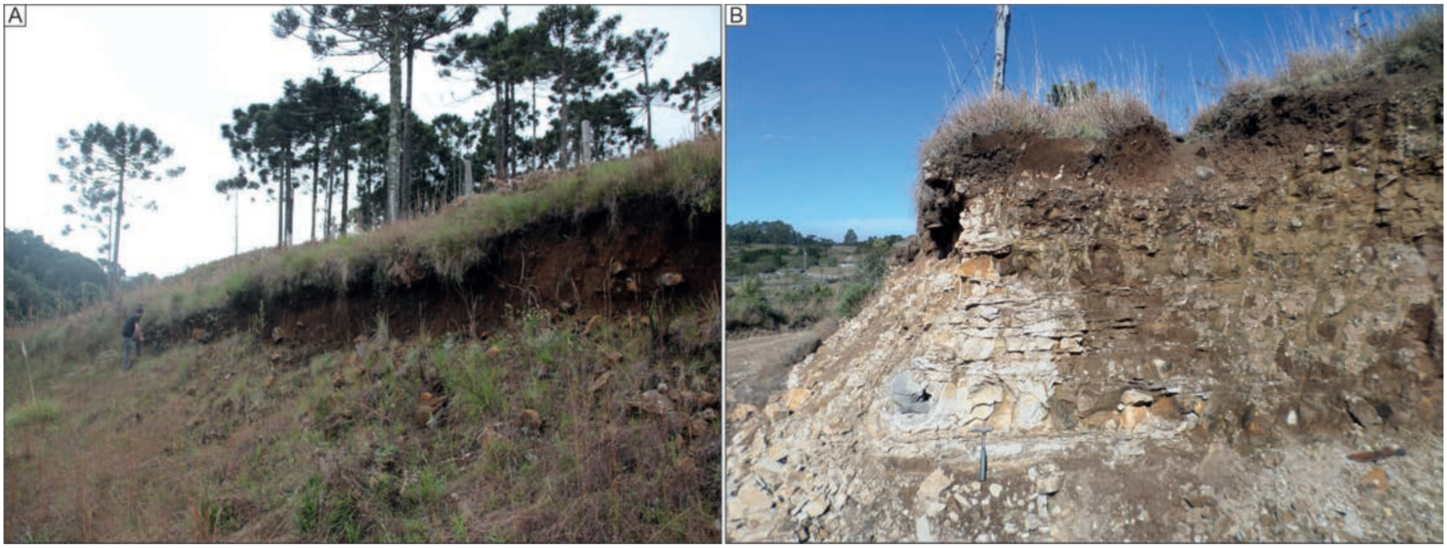

Figure 8. Representative soil profiles: (A) Inceptsols (sample SJE-004) and (B) Entisols (sample SJE-006). São Joaquim, State of Santa Catarina.

Solar Radiation

It is advisable that the vine, depending on the variety, receives between 1200 and 1400 hours/year of solar radiation to complete its vegetative cycle (Sentelhas 1998). São Joaquim receives a mean annual amount of 1832 hours/year. During the growing season (from September to Abril), the mean amount of solar radiation is 1264 hours, allowing the grapes to fully mature.

Viticultural Climate

According to the Geoviticulture Multicriteria Climatic Classification System (MCC; Tonietto and Carbonneau 2004), the viticultural climate of São Joaquim is classified as "Cold, of Cool Nights and Humid" (HI-2, CI+1 and DI-2) (Brighenti and Tonietto 2004). The climatic indices (see Table 9) are very similar to those of Freiburg in Germany, classified as "Cold, of Cold Nights and Humid" (HI-2, CI+2 and DI-2). Although located at very different latitudes (São Joaquim is at 28º17'S and Freiburg is at 48º00'N), both regions have similar night temperatures (12.1ºC in São Joaquim and 11.7ºC in Freiburg), probably due to the effect of altitude on the mean temperature (São Joaquim is at 1415 m and Freiburg is at 269 m).

The grape varieties cultivated in Freiburg include: Spätburgunder (Pinot Noir), Müller-Thurgau, Grauburgunder (Pinot Gris), Weissburgunder (Pinot Blanc), Silvaner (Braatz et al. 2014), Moscato Bianco, Riesling, Sauvignon Blanc, Chardonnay, Merlot, Gewürztraminer, Moscato and Scheurebe (see www.wine-searcher.com). Due to the meteorological similari-

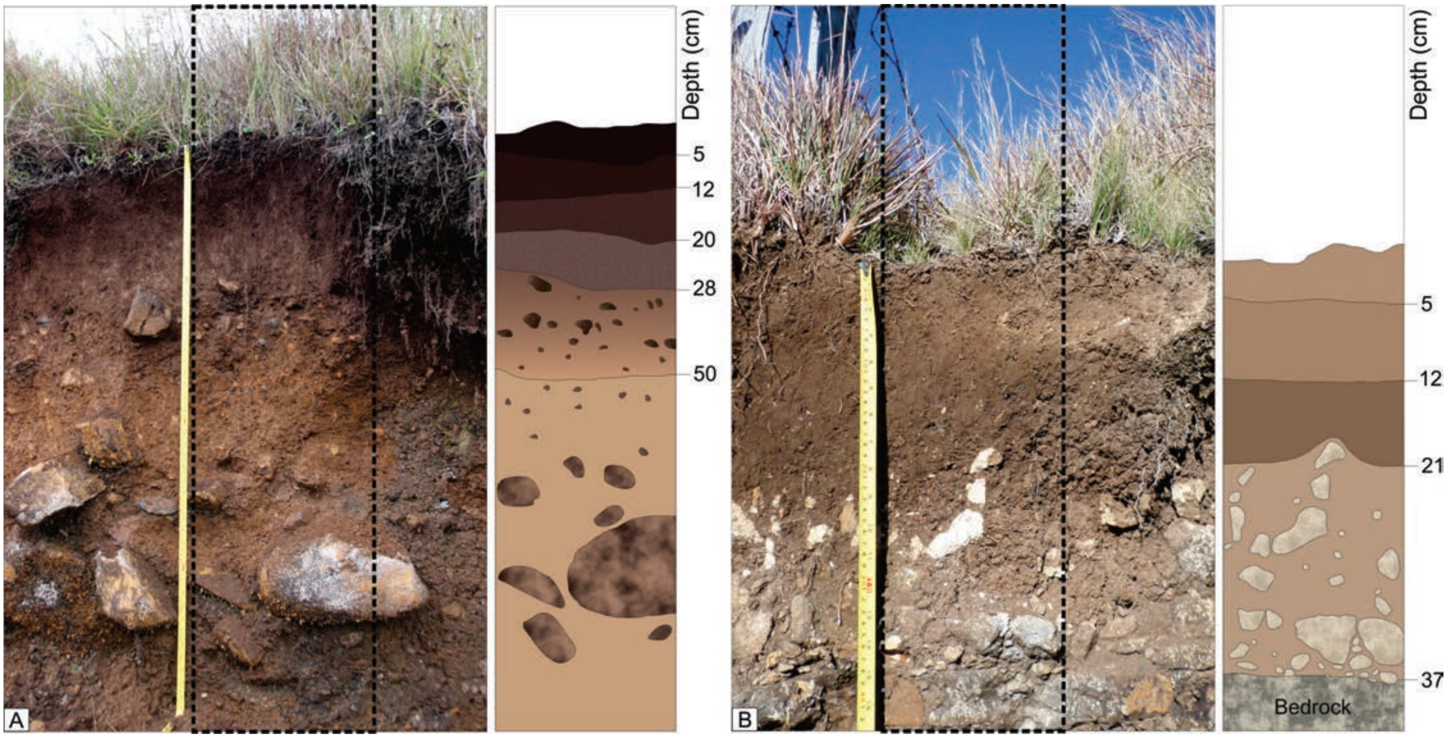

Figure 9. Detailed soil profiles: (A) Inceptsols (sample SJE-004) and (B) Entisols (sample SJE-006). Schematic drawings summarize soil horizons and depth. São Joaquim, State of Santa Catarina.

Table 6. Average chemical composition (major elements in wt.%) of the mafic and felsic volcanic units in the municipality of São Joaquim.

Major elements (wt.%)	Mafic unit	Felsic unit
SiO_2	52.93	68.87
TiO_2	2.05	0.94
Al_2O_3	13.69	12.88
Fe_2O_3	13.87	5.55
MnO	0.19	0.11
MgO	4.54	1.30
CaO	8.57	2.79
Na_2O	2.70	3.09
K_2O	1.16	4.19
P_2O_5	0.30	0.28
Total	100	100

*Data from Besser (2017).

Table 7. Average chemical composition (trace elements in ppm) of the mafic and felsic volcanic units in the municipality of São Joaquim.

Trace elements (ppm)	Mafic unit	Felsic unit
Cr	43	58
Ni	34	7
Ba	366	663
Rb	36	150
Sr	282	129
Zr	163	246
Y	33	43
Nb	15	21
Cu	144	68
Zn	98	75
Co	36	11
V	348	91

*Data from Besser (2017).

ties between these regions, the adaptation of these varieties in the São Joaquim region should be considered. The Sauvignon Blanc variety, which is cultivated in Freiburg, already stands out as one of the best suited to the terroir of São Joaquim.

Physiographic Data

Altitude

In general, a decrease of 0.6°C in the mean temperature occurs for every 100 m of elevation. In Brazil, the climate tends to be hot, so the search for potentially productive high- altitude areas is essential in the main wine-growing regions (Tonietto and Mandelli 2003). São Joaquim has altitudes ranging from 715–1638 m, which means that the region is approximately 4–9°C colder than areas at the same latitude that are located close to sea level. This variation in the temperature modifies the vegetative cycle of the vine, as described by Rosier (2003). This is what makes the Planalto Catarinense viticultural region distinct from the other wine-growing regions in Brazil.

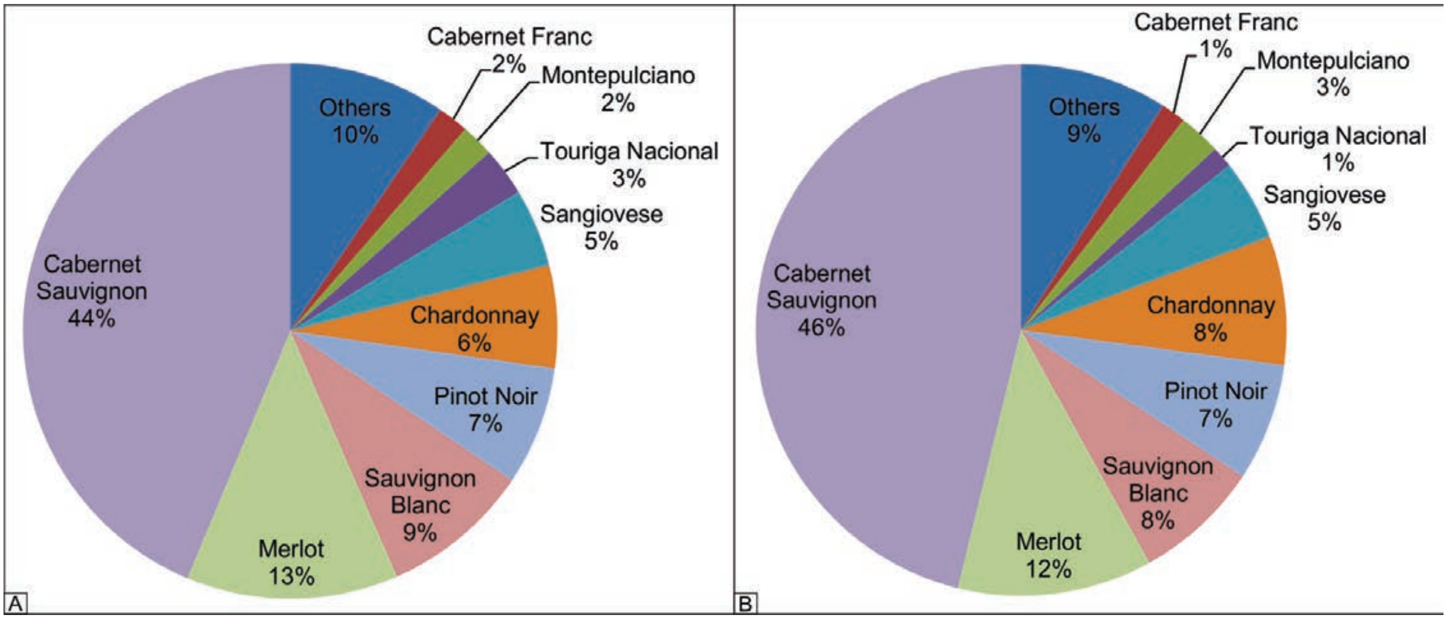

Figure 10. Comparison between the main grape varieties planted in the municipality of São Joaquim: (A) proportions by area (in hectares) and (B) proportions by the number of vines planted. Modified from EPAGRI (2013).

Table 8. The main grape varieties cultivated in the municipality of São Joaquim in terms of area (ha and %) and vines planted (number of vines and %).

Grape variety	Area (ha)	Area (%)	Vines planted	Vines planted (%)
Others	16	10	41,813	9
Cabernet Franc	3	2	6,814	1
Montepulciano	3	2	11,968	3
Touriga Nacional	5	3	5,953	1
Sangiovese	8	5	22,941	5
Chardonnay	10	6	36,229	8
Pinot Noir	12	7	33,299	7
Sauvignon Blanc	15	9	35,65	8
Merlot	22	13	55,065	12
Cabernet Sauvignon	73	44	214,103	46
Total	168	100	463,835	100

*Data from EPAGRI (2013).

To be part of the Santa Catarina ”fine wines of altitude” collective brand, the vineyard must be located at altitudes of at least 900 m (Dortzbach 2016). According to the data analyzed from EPAGRI (2013), no vineyards in São Joaquim are located below 1093 m. The majority of the vineyards (61%) are located at altitudes between 1200–1300 m (Table 10), meaning that all vineyards in the region are influenced by the effects of altitude.

Declivity

The risk of erosion and the difficulty of mechanization are issues for slopes with declivities higher than 20% (Jordan et al. 1981). Slopes with declivities lower than 3% may be more amenable to mechanization, but may present problems related to poor draining of soils (Dortzbach 2016). Slopes with declivities between 3–20% are generally considered to be the most suitable for viticulture. According to the data analyzed from EPAGRI (2013), about half the vineyards (51%) in São Joaquim are located on slopes within this range of declivity (Table 11).

Orientation

In the Southern Hemisphere, the orientation of the slope towards the north allows the vines to receive solar radiation for a longer period of time and also protects the vines from cold southern winds (Melo 2003). According to the data analyzed from EPAGRI (2013), most parts of the vineyards in São Joaquim are located on slopes facing north (23%), northeast (13%) and northwest (18%) (Table 12). Broadly north-facing orientations account for 56% of the vineyards by area.

Pedological Data

In the cultivation of grapes, preference is given to soils with a loam texture (30–50% sand, 30–50% silt and 10–30% clay, according to Santos et al. 2013), well drained, with pH ranging from 5 to 6 and soil organic matter (SOM) contents of at least 2% (Melo 2003). The root system of the vine rarely exceeds 120 cm, with 90% of the roots distributed in the first 60 cm (Dortzbach 2016). In São Joaquim most of these characteristics, including pH and depth, are found in the inceptsols derived from the basalts and basaltic andesites of the mafic volcanic unit.

Geological Data

According to Jackson (2008), some cultivars are more adapted to soils derived from rocks of specific composition, but evidence on these aspects is still circumstantial and there is no experimental evidence. In this preliminary study of the munic-

Table 9. Geoviticultural Multicriteria Climatic Classification (MCC) System indices for São Joaquim (Brazil) and Frieburg (Germany).

		Location			Geoviticulture MCC System[1]		
Country	**Region**	**Latitude**	**Longitude**	**Altitude**	**HI**	**CI (°C)**	**DI (mm)**
Germany	Freiburg	48° 00' N	7° 51' E	269 m	1684	11.7	200
Brazil	São Joaquim	28° 17' S	48° 55' W	1415 m	1714	12.1	200

*Data from EMBRAPA (2008).

[1] Geoviticulture Multicriteria Climatic Classification (MCC) System climatic indices (Tonietto and Carbonneau 2004):
Heliothermal Index – HI: very cold (HI -3: HI < 1500), cold (HI -2: 1500 < HI 1800), cool (HI -1: 1800 < HI < 2100), warm (HI +1: 2100 < HI < 2400), hot (HI +2: 2400 < HI < 3000) and very hot (HI +3: HI > 3000).
Cold Night Index – CI: cold nights (CI +2: CI < 12°C), cool nights (CI +1: 12°C < CI < 14 °C), warm nights (CI -1: 14°C < CI < 18°C) and hot nights (IC +2: CI > 18°C).
Dryness Index – DI: very dry (DI +2: DI < -100 mm), dry (DI +1: - 100 mm < DI < 50 mm), sub-humid (DI -1: 50 mm < DI < 150 mm) and humid (DI -2: DI < -150 mm).

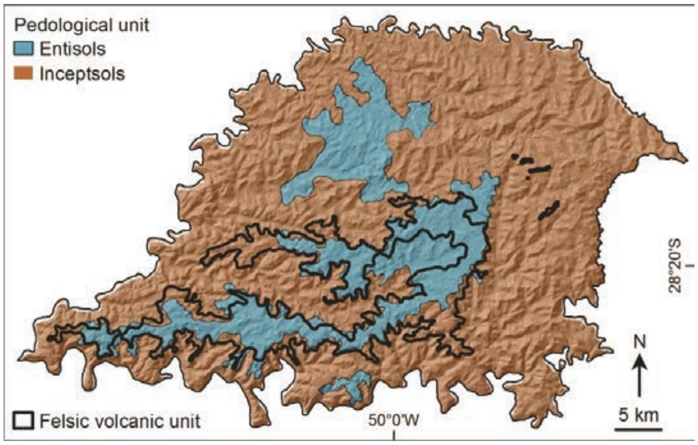

Figure 11. Pedological map of the municipality of São Joaquim, modified from Potter et al. (2004), showing the correlation between the entisols and the felsic volcanic unit.

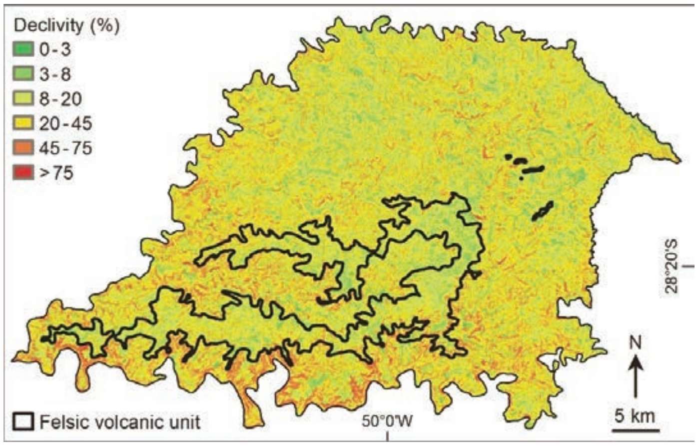

Figure 12. Declivity (%) map of the municipality of São Joaquim, modified from SDS (2010), showing the correlation between the slopes with low declivities and the felsic volcanic unit.

ipality of São Joaquim, we suggest that there is an influence from geology upon pedological and physiographic properties, and thus on the viticultural potential of the region.

Table 10. Area occupied by the vineyards (km^2 and %) at various altitudes in the municipality of São Joaquim.

Altitude (m)	Area (ha)	Area (%)
< 1100	1	1
1100 – 1200	40	24
1200 – 1300	103	61
1300 – 1400	18	11
> 1400	6	3
Total	168	100

*Data from EPAGRI (2013).

Table 11. Area occupied by the vineyards (km^2 and %) at various slope declivities in the municipality of São Joaquim.

Declivity (%)	Area (ha)	Area (%)
0 – 3	12	7
3 – 8	32	19
8 – 20	54	32
20 – 45	62	37
45 – 75	7	4
> 75	0	0
Total	168	100

*Data from EPAGRI (2013).

Across the municipality of São Joaquim, there is a correlation between the mafic volcanic unit and the development of inceptsols, and between the felsic volcanic unit and the development of entisols (Fig. 11). This correlation is confirmed by the physical and chemical properties of the soils analyzed in this study. Soils developed from mafic volcanic rocks (12 samples analyzed from 2 soil profiles) tend to be thicker (> 150 cm), have a clayey texture, and an average pH (water) of 5.52. They have an average content of 146 ppm Al^{3+}, 663 ppm Ca^{2+} and 271 ppm Mg^{2+}. Soils derived from felsic volcanic rocks (40 samples analyzed from 7 soil profiles) tend to be thinner

Table 12. Area occupied by the vineyards (km^2 and %) at various slope orientations in the municipality of São Joaquim.

Orientation	Area (ha)	Area (%)
North	39	23
Northeast	26	15
East	20	12
Southeast	12	7
South	11	7
Southeast	13	7
West	17	10
Northwest	30	18
Total	168	100

*Data from EPAGRI (2013).

(< 100 cm), have a clayey texture, and an average pH (water) of 4.68. They have an average content of 509 ppm Al^{3+}, 80 ppm Ca^{2+} and 67 ppm Mg^{2+}. Considering these data and the previous studies, the mafic volcanic unit in the municipality of São Joaquim appears more likely to provide inceptsols suitable for viticulture.

There is also a correlation between the felsic volcanic unit and the slopes with lower declivities and between the mafic volcanic unit and slopes with higher declivities (Fig. 12). Given that previous studies suggest that the 3–20% declivity interval is most suitable for viticulture, areas underlain by the mafic rocks are more likely to satisfy this criterion. The steeper slopes associated with the mafic volcanic rocks are likely related to the presence of thicker lava flows, whereas the felsic rocks consist of thinner tabular flows on the top of the volcanic pile. Of the 21 properties dedicated to viticulture in São Joaquim, fifteen properties are located in the mafic volcanic unit, four properties are located in the felsic volcanic unit and two properties have vineyards that include parts of both units (Fig. 13).

CONCLUSION

São Joaquim is the largest viticultural region in the State of Santa Catarina, producing award-winning wines with distinct characteristics due to its unique terroir. The region has 21 properties comprising 268 vineyards that occupy a total area of 168.13 ha and produces a total of 1,100,000 liters of wine per year (estimated). The municipality of São Joaquim includes the 8th highest vineyard in the world (Vinícola Hiragami, located at 1427 m), from which wines won prestigious awards in 2017. These include the *Concours Mondial de Bruxelles 2017* Gran Gold Medal (for the Torii Cabernet Sauvignon of 2013), the *Concours Mondial de Bruxelles 2017* Gold Medal (for the Torii Merlot of 2013) and the *Concours Mondial de Bruxelles 2017* Silver Medal (for the Torii Cabernet Sauvignon of 2008).

The unique terroir of São Joaquim is characterized by low temperatures (mean temperature of 13ºC) and high altitudes (terrains between 715–1638 m, with vineyards located above 1000 m). The mafic volcanic unit in the region is associated with thicker (deeper) soils (inceptsols) with an average pH (water) of 5.52, and also with steeper slopes. In contrast, the felsic volcanic unit is associated with thinner (shallower) soils (entisols) with an average pH (water) of 4.68, developed on more gentle slopes or flatter terrain. The municipality of São Joaquim is dominantly underlain by mafic lava flows and felsic lava flows are less extensive. Both units are suitable for viticulture, but the distribution of vineyards suggests that the mafic volcanic unit is the more favourable, due to the preferential development of inceptsols.

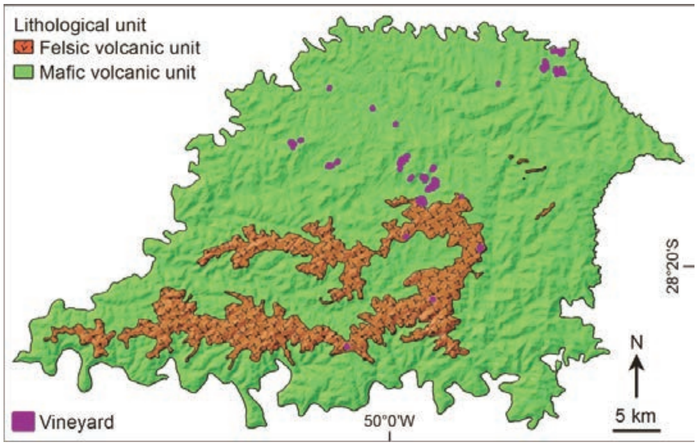

Figure 13. Lithological map of the municipality of São Joaquim, modified from DNPM (1986) and Besser (2017), with the location of the vineyards (purple).

The municipality of São Joaquim has the potential to become a viticultural region of national and international importance, as shown by the example of Vinícola Hiragami. The history of the viticulture in this region has less than 20 years of production. For this reason, research is being undertaken by EPAGRI to detail the physical characteristics of the municipality and test the adaptation of new grape varieties. There remains much to learn and to accomplish.

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ARTICLE

Reading the Rocks Reloaded: A Celebration of the Geological Survey of Canada 175th Anniversary with a View to the Future

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SUMMARY

In 2017, the Geological Survey of Canada (GSC) celebrated its 175th anniversary, just as the 150th anniversary of the Canadian Confederation was celebrated. In many ways, the development of this organization over its long history parallels the exploration and economic development of our country, and these two stories are very closely intertwined. In its early days, the GSC was involved in charting the essential geography of Canada's landmass, and early GSC geologists were involved in some of the discoveries that laid a foundation for our modern resource economy. In the 21st century, the GSC remains at the forefront of geoscience research across the nation, collaborating with many Provincial and Territorial partners and also with academic and industry researchers to expand our knowledge and find ways to sustainably develop our resources. Like all organizations, GSC has evolved over the years, and must continue to do so in response to technological innovation and societal demands. This article provides an overview of where we came from, where we have been, where we are today, and where we hope to go in the future. It is hoped that it will provide a starting point for other articles highlighting some of GSC's more specific scientific contributions over the years, and exploring some of the many characters who colourfully populate its long history.

RÉSUMÉ

En 2017, la Commission géologique du Canada (CGC) a célébré son 175ème anniversaire, alors que l'on célébrait le 150ème anniversaire de la confédération canadienne. De plusieurs façons, le développement de cette organisation au cours de sa longue histoire suit en parallèle l'exploration et le développement économique de notre pays, et ces deux histoires sont très intimement inter-reliées. Dans ses premiers jours, la CGC a été impliquée dans la cartographie géographique essentielle de la masse continentale du Canada, et ses premiers géologues de la CGC ont été impliqués dans certaines des découvertes qui ont jeté les bases de notre économie moderne des ressources. Au XXIe siècle, la CGC reste à l'avant-garde de la recherche géoscientifique à travers le pays et collabore avec de nombreux partenaires provinciaux et territoriaux ainsi qu'avec des chercheurs universitaires et industriels afin d'élargir nos connaissances et de trouver des moyens de développer nos ressources de manière durable. Comme toutes les organisations, la CGC a évolué au cours des années, et doit continuer de le faire en réponse à l'innovation technologique et aux besoins sociétaux. Cet article fourni un aperçu de nos origines, de notre cheminement, de notre situation actuelle et de nos objectifs futurs. On espère que cela fournira un point de départ pour d'autres articles mettant en lumière certaines des contributions scientifiques plus spécifiques de la CGC au fil des ans et explorant certains des nombreux personnages qui peuplent de manière colorée sa longue histoire.

INTRODUCTION

The 2017 GAC–MAC meeting held in Kingston, Ontario, included a special session in honour of the 175th anniversary of the Geological Survey of Canada (GSC), founded in 1842. This session, within the inspiring meeting theme *'Where it all began,'* included several presentations about different aspects of the GSC's long history, and thoughts about its future. This article represents an adaptation from a keynote address that formed part of this session. It is my hope, shared by the editors at Geoscience Canada that other presentations from this session will in time move to formal publication.

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The presentation originally held a longer title: "*Reading the Rocks Reloaded: Canada's and the GSC's Flight on the Arrow of Time, From Eyes on the Stars to Boots on the Ground, and Into the Future.*" This evocative and somewhat poetic title celebrated not only the GSC's momentous achievements but also by extension those of the wider geoscience community in this country, in a year that was also the 150th anniversary of the Confederation of Canada. I will begin by evoking the epic history of the GSC and Canadian geoscientists through a multi-generational perspective. Then, I will summarize the geographical and geological exploration of Canada over many decades, and the discoveries of some of the most spectacular landscapes and diverse, long-ranging geological records in the world. Finally, I will offer some perspectives on the challenges ahead for geoscience in this country and the direction that the GSC is taking to address them.

Recently, the GSC celebrated its 175th anniversary with joyful in-house gatherings of employees and friends, naturally coupled with some music and speeches. We did this to mark the traditional April 14th 'birthday' of the GSC, commemorating the day in 1842 on which William Logan accepted his letter of employment from the Province of Canada, following the recommendation of several eminent British geologists. He subsequently traveled to Canada and turned up at the government office in Kingston in late August 1842, nearly a year after the Legislature approved the funding of the survey in 1841. It was to fulfill an ambitious legislated mandate:

> *"… be it resolved that a sum of money not exceeding £1500 sterling be granted to Her Majesty to defray the probable expense in causing a Geological Survey of the Province of Canada."* (Canada (Province), Legislative Assembly 1841).

The original intent was to have a completed survey in a couple of years, but given Canada's vast geography, changing geologically-based priorities and the wisdom of successive parliaments, the work has taken longer than originally thought, and is still ongoing. 175 years later, there does not seem to be an end in sight to the geological surveying of Canada. In conjunction with the Provincial and Territorial geological surveys, the GSC has now mapped the majority of Canada`s landmass, describing the surface of our land from the American border to its coastal frontiers at a broad regional scale. Nevertheless, we have yet to probe it systematically and substantially at depth and fully document its offshore extensions. In spite of the fact that there is much left to do, we made many discoveries along the way that have served as foundations for the Canadian economy. The understanding of Canada's geological architecture and resources involved many organizations, people and cultures. The initial efforts of the GSC were aided greatly by the deep indigenous traditional knowledge about the geography of this vast land. Indigenous people traded native copper from the Great Lakes region, as well as chert from Labrador, millennia before Europeans even dreamed of sailing this far west. These indigenous people also played a key role in supporting the exploration of Canada, in teaching survival skills in the difficult boreal wilderness, in sharing their own knowledge of the geography of the continent, and in accompanying the explorers as guides, hunters, warriors, and as co-leaders. This body of knowledge combined over time with the technology of European newcomers, and with the ideas of natural philosophy that emerged and evolved in the late 18th century to form the principles of modern Geological Science.

Let`s reflect on why we celebrate these 175 years. What does such an anniversary mean? It is another slice of 25 years in the history of an organization. It is common to think of 25 years as the length of a typical human generation, so we are celebrating seven generations of geoscience in Canada, and entering the eighth. This is a chance to look at the past, consider the present and peek into the future. In the span of seven geoscience generations, we have achieved great things that we can reflect upon, and find in them the inspiration to forge ahead towards a future of sustainable land and resource development that will sustain generations to come.

The present-day GSC is home to some 400 employees, spread from coast to coast to coast, from Dartmouth in Nova Scotia to Sidney in British Columbia, and to Iqaluit in Nunavut. Friends of the Royal Canadian Geographical Society (RCGS) awarded the GSC with a Gold Medal in November 2016 at their annual Gala held at the Canadian War Museum. The event, attended by a great assembly of friends, was a very moving and joyful occasion. Highlights included awards to present and former GSC employees of three more Gold Medals, to Paul Hoffman, Denis St-Onge and Marc St-Onge. The Massey Medal was awarded to Stephen Blasco. Having had the honour of receiving the Gold Medal on behalf of the GSC from the Minister of Natural Resources, the Honorable Jim Carr, and the President of the RCGS, Paul Ruest, I made it my mission for the year to bring it to our staff to hold as I visited all the GSC offices. It was my way of underlining their contributions and to acknowledge the importance of the professionalism embraced by the present employees of the GSC. Many enjoyed a 'selfie' with their Gold Medal, from which a great mosaic was made (Fig. 1). This medal is not only for the current GSC generation, but also for the past generations, those before us, and is a reminder that we stand on the shoulders of giants in science, whose achievements will hopefully be outlined and assessed by other papers.

FROM RAGS TO RICHES: THE ROLE OF MINERALS IN CANADA'S PROSPERITY

Through the hard work of generations, Canada's geology has become the foundation of our economic prosperity including minerals, oil and gas, soils, fertilizers and construction materials for our roads, harbours, buildings and so many other things. Every Canadian knows, or should know, the value of our natural resources in economic development.

Understanding the geology of some 17 million square kilometres of onshore and offshore territory is a never ending task – What do history and geology tell us of how we got from where we were 175 years ago to where we are now? Recall that in 1842, when the government started a one-person geological survey, Canada had no substantial mining production beyond minor coal seams in Nova Scotia, and no certain knowledge of whether it had any potential. Today, Canada has a thriving

Figure 1. Some of the GSC staff holding the Royal Canadian Geographical Society (RCGS) Gold Medal awarded to the GSC in November 2016. A 'GSC and William Logan' medallion was also distributed at the time to all the RCGS gala participants. It has since been turned into a 'golden' version that is awarded annually to meritorious staff of the GSC.

economy; ranked as the second best mining exploration destination in the world, with the majority (57%) of global mining finance in 2016 coming from the Toronto and Vancouver Stock Exchanges. Canada ranks in the top five countries for the global production of 13 major minerals and metals: we are first in potash, second in uranium, nickel and niobium, third in cobalt and platinum group metals, fourth in salt, sulphur and tungsten, fifth in diamonds, graphite and gold, and we are the sixth largest global producer of oil. Current production is close to four million barrels per day, and we have the third largest oil reserves in the world. In addition to mineral production, Canada is also important in the processing of resources from elsewhere, such as aluminum. The difference between what we knew of in 1842 and what we now enjoy is so vast that it is hard for the layperson to imagine that it all began when Logan set out on a simple field expedition to Nova Scotia and Gaspé in 1843 to look for coal and other minerals. Did geoscience and the GSC have a major role to play in Canada's development as a resource giant? The answer is of course complicated but also interesting, and in essence, it is a solid 'yes.'

The GSC's long history can be found in several interesting accounts, including the detailed and well-researched book "Reading the Rocks" (Zaslow 1975). I strongly encourage readers to explore Zaslow's fascinating accounts of the epic expeditions and resulting discoveries of the 'founding five Directors'. From Logan to his successors Alfred R.C. Selwyn, who led the GSC for 25 years, (see Figure 2 for an example of early GSC innovative technology application led by him), George M. Dawson, who surveyed the southern Prairies, British Columbia and Yukon, (Fig. 3), Robert Bell, famous for his great northern expeditions, (Fig. 4), and Albert P. Low. Low's famous Quebec and Labrador expeditions were the subject of a recent article in Geoscience Canada (Wilton 2018), and we hope that other pioneers in our geoscience will soon be celebrated in a similar fashion.

A GSC tale that has not yet been fully told is that of its achievements and travels on the twisted road of organizational life from the late 20th century to the present day. I will offer here that the GSC and geoscience remain to this day a very important part of who we are as a nation, and have been critical elements of what Canadians have achieved in building this country.

LOOKING DEEP THROUGH CANADA ON THE ARROW OF GEOLOGICAL TIME

My quick and partly metaphorical 'field trip' across Canada will travel on the arrow of geological time and will highlight some interesting facts and observations about our geography, our human history and our geology. Geoscientists have worked long and hard to tease out and document the long geological history of our land, and we have learned a lot, as summarized in Figure 5. Before we depart on this rapid journey, I will refer the lay reader, whom might wish to learn more, to the superb

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Figure 2. Example of early Geological Survey of Canada (GSC) economic geology investigations. In 1880 the GSC contracted for a number of drill holes on the southern prairies to investigate the extent of the lignite deposits exposed on the Souris River. After experiencing considerable difficulty in obtaining suitable timber for the derrick and an engine bed, this hole near Roche Percée was drilled to a depth of 295 feet. Photo Credit: A. Selwyn, second director of the GSC.

book "*Four Billion Years and Counting: Canada's Geological Heritage*" (Fensome et al. 2014) published by the Canadian Federation of Earth Sciences to mark the International Year of Planet Earth.

Canada has a fabulous geological endowment, matched by few other countries in the world. It holds the records of at least 4 billion years of geological history, comprising continental collisions, uplifts, mountain building and continental erosion into vast and long past seas, as well as relics of giant volcanic belts rich with metals. The 'land' was enriched by metallogenic processes that occurred deep in ancient oceans, and was deeply carved by more recent multiple glaciations. Large meteorite impacts scarred it on many occasions, and some of these enriched our legacy of metals and minerals. Few countries in the world have nearly as many layers of rocks, or provide such a nearly continuous record from the early days of Earth to its recent perturbations. From a modern natural hazards perspective, few countries share such a quiet and lucky setting with very few and infrequent large earthquakes, and few active volcanoes. Nevertheless, we are increasingly aware of the risks of major earthquakes and/or tsunami in Canada, and GSC personnel assess and monitor such hazards, just as we seek to understand the past.

Figure 3. G.M. Dawson and party standing in front of building in Fort MacLead, Alberta, 1879. Dawson became the third Director of the Geological Survey of Canada (GSC) in 1895 after an epic career as a staff geologist that started in 1875 when he joined the organization. He wrote several milestone reports based on extensive field work with parties such as this one. Dawson worked for the British North American Boundary Commission surveying the International Boundary. His GSC reports based on surveys of very remote areas of BC and Yukon were used by prospectors and government geologists during the Yukon Klondike gold rush. Dawson City, Yukon, was named in his honour, as was Dawson Creek, British Columbia.

Figure 4. The Geological Survey of Canada (GSC) has a long history of exploring Canada`s frontier areas and hiring indigenous people for field support, often visiting distant communities such as this one on the shore of Hudson Bay, Manitoba. Photo credit: Robert Bell, fourth Director of the GSC.

Looking much further beyond Earth, and deeper into time, we can see the elemental particles that dominated the moments after the Big Bang and which led ultimately to the coalescence of stars, galaxies and planets. Forces from beyond Earth still reach our planet and can have major influences upon it. As the Earth orbits the Sun, it is bombarded by solar wind particles that can have detrimental effects on infrastructure such as power lines, pipelines, satellites and modern digital communication systems. Every day, GSC geophysicists monitor the solar wind and its effects on the geomagnetic field to issue 'space weather' forecasts to mitigate these impacts. This

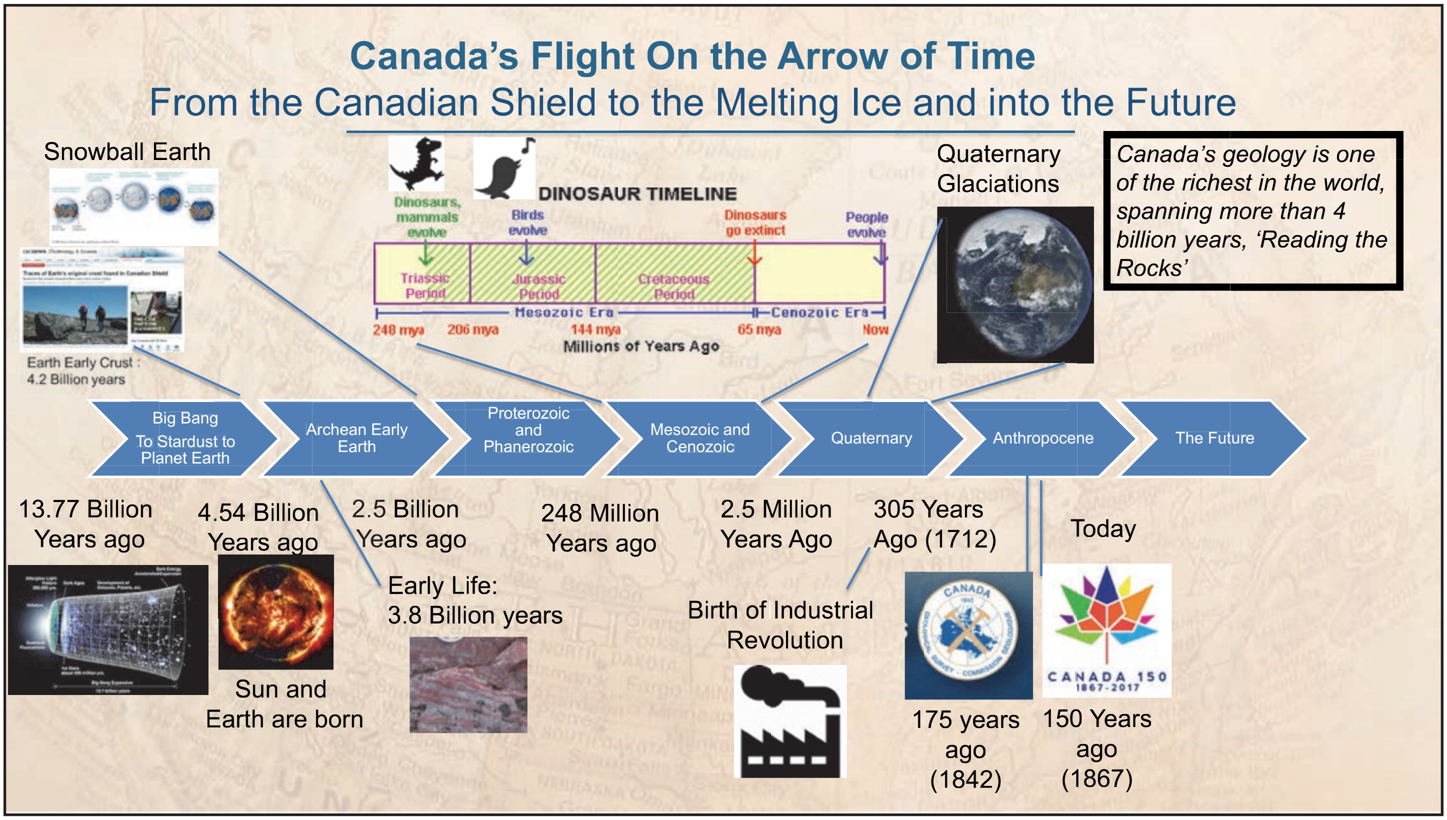

Figure 5. Highlights of Canada's geology and history presented on the "Arrow of time."

advanced system has evolved through several generations, starting in the 1920s with our early basic observations of Canada's geomagnetic field to support magnetic compass-based navigation.

Going back to the Earth's formation as part of solar system, we know that Canada contains the oldest recorded rocks, represented by the 4.0 Ga Acasta Gneiss in the Northwest Territories (Bowring et al. 1989). There may be still older materials, as O'Neil and Carlson (2017) suggest an age of 4.3 Ga for metavolcanic rocks in Northern Quebec. Although based on indirect methods involving extinct radioactive isotopes, and actively discussed in the geoscience community, such results hint at the possible extent of ancient crust in the Canadian Shield. From the same general area comes a report of putative fossilized microorganisms that are at least 3.8 Ga and perhaps as old as 4.3 Ga (Dodd et al. 2017). If the latter inferences and the organic origins of these tiny structures are confirmed, these will place the origins of life on Earth 500 million years earlier than previously suggested by researchers.

If we continue our journey on the arrow of time, we reach the Proterozoic, a long interval of at least 1.5 billion years, marked at its beginning and end by periods of planet-wide glaciation that may have threatened life on Earth, but may also have played a critical role in its development. The longest and oldest of these glaciations, the Huronian glaciation, extending from 2.4 to 2.1 billion years ago, was described in Ontario by Coleman (1907). The relationship between these frigid intervals and the appearance of oxygen in Earth's atmosphere, through the evolution of primitive photosynthetic organisms, is a subject of much keen debate in the geoscience community. Subsequent global glaciations towards the end of the Proterozoic form part of the events labelled as the 'Snowball Earth' (e.g. Hoffman et al. 1998), and may have stalled photosynthesis on Earth, leading to near-collapse of the biosphere. The record of Neoproterozoic global glaciation is well displayed in both northwestern and eastern Canada. However, life survived this crisis, and volcanic gas emissions eventually raised temperatures enough to release the Earth from ice, and begin a new epoch in its long history. The times of the Snowball Earth form the older of two new geological periods added to the global time scale – the Cryogenian and the Ediacaran. The Ediacaran Period witnessed the appearance of the first complex multicellular organisms, including animals. The record of the Ediacaran biota is worldwide, but the earliest and best preserved of these remarkable organisms are in Canada, where they are now preserved as part of the newly declared World Heritage Site at Mistaken Point in southeastern Newfoundland.

Canada has a rich fossil record, which spans the long period from the most primitive unicellular life, to the first multicellular creatures, fossil trees, and many vertebrate forms including dinosaurs, early mammals and the megafauna of the ice ages. We can trace the march of evolution through diversifications and mass extinctions from this remarkable legacy. In Alberta, we have some of the richest dinosaur fossil beds in the world and the richest oil deposits, the oil sands.

GSC geologists have minutely documented and synthesized the richest global records of past glaciations (e.g. Dyke 2003). These are of critical importance in understanding the natural fluctuations of our planetary climate, but also played a significant role in the discovery of mineral resources, as discussed below.

From prehistoric times to the mid-19th century, natural resources extraction and trade through the territory that is now Canada was mainly represented by the harvesting of wildlife (fur trade and cod fisheries), agriculture and forestry. No substantial metal mines, gem, or petroleum deposits were developed until the middle of the 19th century, aside from coal in Nova Scotia. The discovery and development of numerous mineral and petroleum deposits in the mid and late 19th century and in the 20th century propelled Canada's economy into an enormous expansion, and translated into rapid GDP growth, allowing the country to fund the significant infrastructure and socioeconomic benefits that we enjoy today. Canada contains the largest component of the Canadian Shield (also known as the Laurentian Shield) which many would consider the most resource-endowed section of the Earth's crust. Exploration of the Canadian Shield, has unearthed some of the richest gold and base-metals camps in the world, and it also contains substantial deposits of nickel, uranium, cobalt and many other valuable industrial commodities. Exploration continues today, guided by our knowledge of the origins and distribution of metal deposits, and discoveries of many types are still being made. Beyond the confines of this ancient core to our country, valuable resources occur in the Appalachian mountains of eastern Canada, and throughout the Rockies and other western Canadian regions, where huge deposits of copper and molybdenum are related to past volcanic and igneous processes that resemble those operating today in western South America. The quest for minerals sometimes leads to totally new developments, such as the discovery of valuable diamond deposits in Canada's north, notably in the Northwest Territories, Ontario and Quebec. The story of Canada's arctic diamonds is a great example of detective work by geologists and prospectors, but the wider knowledge of our ice-age history was equally important in finding mines such as Diavik, which produces gems worth $2 billion every year.

Early mineral discoveries in Canada commonly involved traditional indigenous knowledge of the land, and our First Nations communities continue to play an important role in prospecting for resources. The development of resources brings benefits to indigenous communities, through impacts and benefits agreements and direct employment opportunities. In the modern world, the successful and environmentally sustainable development of resources requires consultation and cooperation between stakeholders, and much progress has been made in this respect.

This field trip through deep geological time has highlighted the great knowledge derived through scientific and technical efforts over the last 175 years, and the Geological Survey of Canada has played an important role throughout that time. We have not been alone in this, and cannot claim credit for every discovery or insight, but we have provided much foundation knowledge, and a framework for the research and exploration efforts of many others. Canada is a unique geological destination from the perspective of fundamental scientific research, and it is one of the world's most active mineral exploration destinations. This reflects its many natural geological endowments, and its welcoming investment climate, but it also reflects the quality and availability of geoscientific data, and a history of technical innovation in these fields. These same attributes have made Canada the largest source of worldwide funding for mineral exploration, and make Canadian exploration and service companies important all across the globe.

EYES ON THE STARS: EXPLORING AND MAPPING THE OUTLINE OF CANADA BEFORE 1842

The quest for mineral resources and their exploitation started long before European explorers came to the eastern reaches of Canada. Indigenous people traded native copper from the Great Lakes region, chert from Labrador and many other commodities for thousands of years. The Ramah chert quarry in northern Labrador and the Fleur-de-Lys soapstone quarry in northern Newfoundland are amongst the oldest mining ventures known anywhere in the so-called 'new world.' In the 19th century, much remained to be systematically reported in terms of scientific examination, and even the basic geography of many remote areas was not established from surveying. Early maps and exploration efforts depended to a large extent on the traditional knowledge and support of the indigenous people of Canada, a foundation that the GSC built upon, and continues to value.

Shoalts (2017) notes that the early geographic exploration and mapping of Canada, to the mid-19th century, was done through momentous expeditions led by the likes of the Viking Eric the Red , Jacques Cartier, Samuel de Champlain, Samuel Hearne, John Franklin, le Sieur de La Vérendrye, and Alexander McKenzie. These expeditions were fraught with danger and challenges, and were aided by the support and guidance of indigenous peoples, such as Matonabbee and his clan, who guided Samuel Hearne's expeditions.

Common among early European explorers were several drivers: a desire for recognition, fame or 'stardom,' an avid curiosity and thirst for knowledge, and an appetite for wealth (extending territory for fur trade, or finding a trade route to the Pacific). In addition, separate from those seeking fame and wealth, missionaries and other explorers sought religious converts. It is unlikely that they could have sought such goals without indigenous peoples teaching them survival skills in the difficult boreal wilderness, sharing their own geographical knowledge, and accompanying them as guides, hunters, and sometimes as co-leaders. The mapping achieved through these expeditions is impressive, given that through most of the 17th and 18th centuries, the bulk of the exploration was undertaken using birch bark canoes, navigating up and down streams and coasts, using only crude celestial navigational instruments.

These early geographic explorations, continuing into the mid-19th century, achieved three important outcomes. Such efforts provided a broad outline of the coasts, major rivers and mountains, and limits of the continent, as we know it now, with the exception of the Arctic Islands. They led to a series of large settlements in southeastern Canada, serving as bases for later establishing the small communities and fur trade posts that dotted the land in the west and the north. Last, but not least, a relatively prosperous colonial economy and society grew up based on agriculture, forestry, fur, and fisheries, with an ever-expanding land base. This territorial expansion was, of course, driven by a fierce competition between Britain and the emerging American Republic, based on the colonial demand for resources and immigration.

By 1842, there were still little or no mineral resources developed in Canada apart from some coal, quarried stone and various artisanal uses of clay and sand. Only a few instances of metalliferous ores, such as the bog iron of Trois-Rivières and the native copper deposits that served to make tools and jewellery used by indigenous peoples, had been developed economically on a small scale. Coal mining had begun in the early 18th century near Louisbourg, Nova Scotia, but its exploitation remained at a similarly small scale.

PUTTING BOOTS ON THE GROUND: THE CREATION OF THE GEOLOGICAL SURVEY OF CANADA

Between 1825 and 1850, coal mining in Nova Scotia expanded, spurred by an appropriate licensing scheme and industrial demand. An equivalent boom in coal mining in the British Isles was driven by the steam engine and the industrial revolution. This led to the first meticulous mapping of the geology of Great Britain through the efforts of William Smith, whose first national-scale geological map, by far the most accurate of its time, was published in 1815. This map showed the usefulness of mapping to predict and locate the mineral resources of the country (see Winchester 2001 for the story of the "*Map that Changed the World*") and most certainly set the stage for the creation of the Geological Survey of Canada and geological surveys across most industrialized countries through the 19th century and into the early 20th century.

William Logan, who had participated in the mapping of Great Britain with his mentor Henri de La Beche, was chosen to found the GSC. Canadian-born, but educated in Britain, he was hired to further the economic expansion of the Province of Canada (present-day Ontario and Quebec), by identifying and assessing its mineral resources. Coal, known to occur in Nova Scotia but not yet in the Province of Canada, was of special interest, because it was clearly essential for economic expansion.

William Logan must surely had a humbling experience in considering the challenge ahead in surveying a country as large as the Province of Canada. As he wrote in 1842:

> *"The extent and nature of the territory will render the task a most laborious one; but I am fully prepared to spare no exertion of which I am capable, to render the work, when it is completed, satisfactory to those who have instituted the examination, and creditable to myself. I am especially anxious to bring the investigation to a conclusion in as short a time as a due regard to geological truth and the applications of the science will permit"*(Logan 1843).

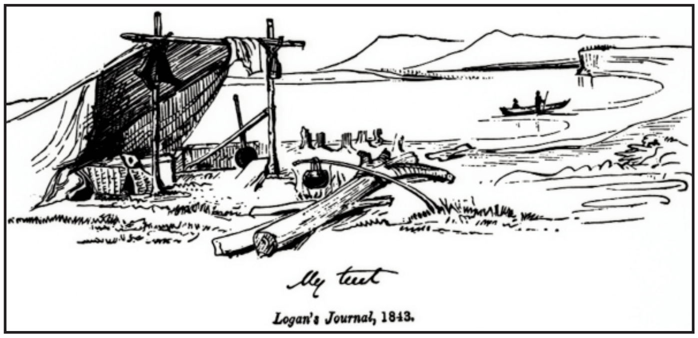

Figure 6. Drawing by William E. Logan entitled "My tent" excerpted from his journal, 1843. The reader can find more on this and other interesting facts about the Geological Survey of Canada on a new website entitled *The History of the Geological Survey of Canada in 175 Objects*.

Logan met this task head-on, taking up his duties in Kingston, Ontario, on April 14, 1842 (which we now mark as the GSC's traditional 'birthday'), starting his fieldwork in the summer of 1843, and surveying geology along the coasts, lakes and streams of Quebec, Ontario and Nova Scotia. This was done by canoe and foot traverses across fields, forests, and mountain ranges. Logan used only a tarpaulin as a tent (Fig. 6), had only a few bags for his possessions, carried just a compass and a hammer, and had the assistance of only a few local hires. After roaming the coasts and rivers of parts of Nova Scotia and Quebec, and up the St. Lawrence Valley, he was not able to report finding any coal seams in the Province of Canada. He was, however, able to report on a number of mineral occurrences and much geology worthy of further investigation.

As we look at todays more elaborate and structured GSC field practices, the simplicity of the tent retains an appeal for many. It is a way to move around lightly and quickly, and to gather data efficiently on the land. We now have computers and all sorts of technological marvels such as GPS and portable X-ray fluorescence devices, but fundamentally, we still rely on direct observations to gather data, collect rock samples and tell the story of 'what's out there.' Even with sophisticated remote surveying and detection techniques, field work remains vitally important to the GSC and it is a method that we prioritize to this day. Although other types of data are undeniably valuable in what we do, field work remains an efficient empirical approach to unravelling many geological puzzles.

THE GEOLOGICAL MAP OF CANADA: THE WORK OF MANY GENERATIONS

By 1864, in less than 25 years or one generation, Logan had produced a map of the southern part of Canada and the adjacent United States, which was a remarkable achievement (Logan 1864; Fig. 7). This map, like so many of the objects described in a new portion of the *science.gc.ca* website - *The History of the Geological Survey of Canada in 175 Objects* (George Plant and collaborators 2017) – is an iconic part of the history of Canada. If Smith's geological map of England 'changed the world,' we can safely say that Logan's geological map changed Canada's future. In fact, his map, made jointly with US geolo-

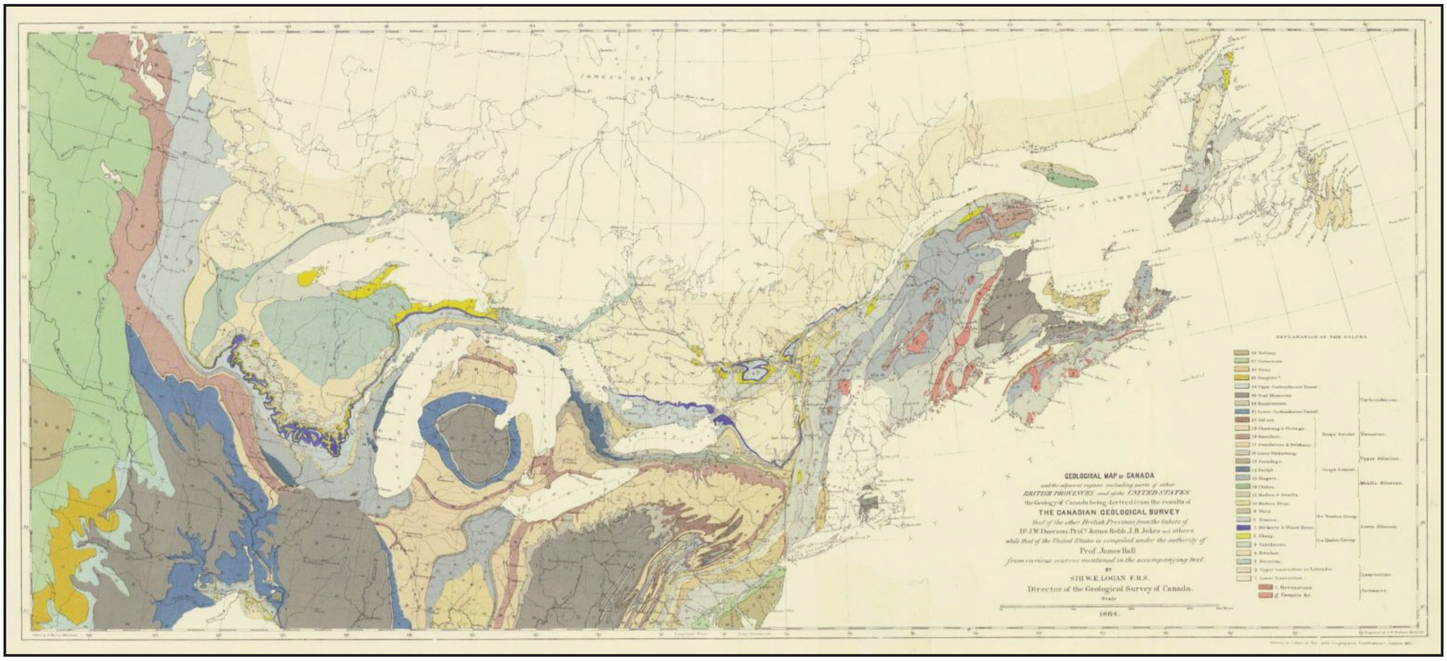

Figure 7. Geological map of Canada by Logan (1864).

gist James Hall, is a fully integrated cross-border map of Canada and the USA. The map features all the main elements of the geology of Eastern North America: the Appalachian fold and thrust belt, the St. Lawrence Lowlands, and the great basins of the Midwest. It is an amazing feat given that it was done with only the help of a compass, a hammer, and some basic surveying tools such as a simple wheel to measure distances and generally without the benefit of any topographic base map. He produced one map at 1" to 150 miles and another one at 1" to 25 miles, which compares to the maps of William Smith that one can see today at the British Museum of Natural History.

Logan and his scientists also had a knack for striking the imaginations of the public and policy-makers by putting together collections and displays for events such as the Great Exhibitions of London and Paris in 1851 and 1852. In 1855, only 13 years after he founded the GSC, Logan earned a knighthood from Queen Victoria, one would think in large part because his geological contributions to the exhibitions were so well presented and captivating on the world stage.

Since 1864, the GSC has produced several new versions of the geological map of Canada, one every 25 years or so. The most recent version published in 1996 was under the supervision of past Chief Geologist John Wheeler (Wheeler et al. 1996). The GSC is now looking at the development of the next generation of the map of Canada, under a project that we have labelled 'Canada 3D.' Having reached the frontiers of the land in two dimensions at a broadly regional near-surface level, we are starting to map deeper and project the geology under our feet, moving to another frontier. It is the GSC's primary mission to document and understand Canada's long geological history, but knowledge of the geology of Canada has not been achieved by the GSC alone. It is the culmination of joint efforts over multiple generations by the community of geoscientists from the geological surveys of the provinces and territories of Canada, academia and the private sector. The provincial and territorial surveys only really took flight after the constitutional arrangements of 1867 that devolved responsibilities over natural resources to these jurisdictions. Every Province and Territory in Canada, aside from Prince Edward Island, has a geological survey. After some consideration of abolishing the GSC in the 1870's and again in the 1990's (Findlay 2010), sound thinking prevailed, and agreements were forged to instead foster federal-provincial cooperation centred on common geoscientific objectives. Although there were naturally some disagreements about priorities, the intent and workings of the Intergovernmental Geoscience Accord (Canada Mines Ministers 2012) now ensures cooperation and complementary roles for the federal and provincial/territorial surveys, and has proved successful in doing so (Fig. 8). This cooperation is strengthened by the participation of geoscientists from the private sector and academia in many larger projects.

A VIEW TO THE FUTURE

Lebel (2010) presented some views on drivers that will shape Canadian geoscience in the 21st century. These include a renewed race for minerals and energy on the Canadian frontiers in a resource-hungry world, stock market swings and economic cycles in times of financial and commodity price upheavals, globalization and the growth of junior mining companies. Wider influences include concern over climate change and other environmental issues, the globalization of science, onshore and offshore indigenous land claims, and the increasingly global competition for the tight supply of scientific professionals.

Some new drivers have emerged since 2010, and others have changed in importance, but I suggest that this list still applies today. We can perhaps add the decline of the traditional print news media and the emergence of social media, and a

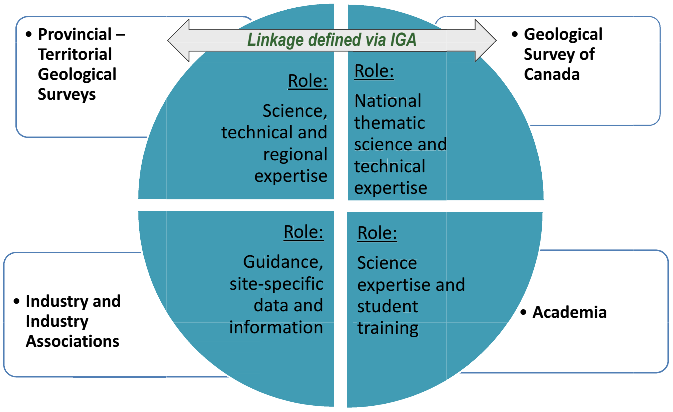

Figure 8. Canada`s geoscience 'ecosystem' in relation to the Intergovernmental Geoscience Accord 2012 (IGA). As described in the IGA, Canada's geological surveys were: "*Initially established to encourage and regulate the development of mineral and energy resources, the geological surveys in the 21st century deliver public geoscience programs that contribute to a broad spectrum of economic, health and safety, environmental, and other public policy issues. The Intergovernmental Geoscience Accord provides a framework for cooperation and collaboration among the federal, provincial and territorial geological surveys. Cooperation and collaboration minimize overlap and duplication, enhance synergies among jurisdictions to resolve regional geoscience problems, and facilitate optimal utilization of resources.*"

general decline in the public's confidence in public and private institutions and authorities (Johnston 2017). Technological change will continue to drive innovation and the need for new geoscience, because new technologies increase the demand for some minerals and metals (e.g. lithium and rare-earth elements), and new exploration methods and models require specific information that may not have been acquired by earlier work.

Geoscientists are making increasing use of revolutionary technologies. For example robotics, drones, microsatellites and distributed sensor networks are revolutionizing remote sensing, and handheld XRF devices provide analyses 'at the outcrop' rather than waiting months for lab analyses to be completed. Three-dimensional basin mapping allows increased understanding of the geology required for petroleum exploration, but also for carbon capture and sequestration. Biology and geoscience intersect in the evaluation of DNA fingerprinting of oil eating bacteria and Genetically Modified Organisms that could mitigate pollution problems from resource extraction. Modern computer and digital processing allows easier three-dimensional geological modelling, and neural networks, machine learning and artificial intelligence help us to find and understand patterns in our data.

Geoscientists are 'knowledge integrators' who read the rocks and discover in them stories and hidden treasures that they can relate in words and illustrations. These stories still need to be published as open data sets and scientific papers for the scientific community to build upon, but other media (e.g. YouTube videos) give us new tools and ideas for public education and data dissemination. These new approaches need to continue and grow if we are to form bonds between scientists and the wider communities that can benefit from geoscience surveys (Groulx et al. 2017). Without renewed and innovative efforts in Earth Science public education, it is likely that social consensus on difficult issues such as the subsurface sequestration of waste carbon, hydraulic fracturing ('fracking'), or enforcement of standards and regulations for construction on flood plains and coastal areas will remain elusive. Special attention will need to be given to social-media approaches and modern methods to present Earth Science and Engineering concepts in a manner that is meaningful to citizens who do not have scientific backgrounds.

A STRATEGIC PLAN FOR THE GEOLOGICAL SURVEY OF CANADA FOR 2018–2023

The first goal for the GSC stated in its new five-year strategic plan (Geological Survey of Canada 2018) is the sustainable development of Canada's natural resources. This links the long-established mandate of understanding Canada's remarkable geology to the practical application of such knowledge to generate socio-economic benefits through sustainable resource development and environmental protection. This continues the long tradition of scientific research to understand geological processes and develop new scientific methods, and combines it with the use of new technological methods for surveying and detection. We will continue to develop the core geoscience knowledge that will remain critical to the success of sustainable mineral exploration, support the development of low carbon energy such as geothermal, and inform land decisions regarding the management and protection of water resources. The geoscience data from such efforts is also critical to other stakeholders, such as indigenous peoples and communities that need such knowledge to manage their land base and make decisions about mineral and other resource developments, and understand the impact and cumulative effects of development.

A second important goal for the GSC is to continue investigations aimed at natural hazard risk reduction, including floods, earthquakes and landslides, to reduce the steadily increasing human and infrastructure costs of natural disasters in Canada. In addition to potential hazards related to the natural geological environment, we must increasingly assess the effects of climate change on the potential for such events, and on the vulnerability of affected locations.

A third objective for the GSC is to pursue the advancement of framework geoscience knowledge, in the form of targeted maps and ancillary databases, to provide a sound basis for decision-making and policy initiatives for both onshore and offshore areas. The initial objectives include first completing the Geomapping for Energy and Minerals (GEM) program aimed at Canada's northern regions, and completing Canada's submission to the UN Commission on the Limits of the Continental Shelf. The GSC's role in marine geology is a very important one, and is well illustrated by Figure 9, which highlights our cooperation with Sweden, even in the face of the legendary rivalry of our countries in ice hockey! In the longer term, we seek to develop the terms of a new flagship public geoscience program that could be delivered jointly with provinces, territories, and universities.

In all these areas, the GSC intends to remain at the leading edge. Just as we pioneered protocols for the use of portable XRF in the field, and have been a leader in remote predictive

Figure 9. (a): Photograph of the Canadian icebreaker Louis St. Laurent and the Swedish icebreaker Oden near the North Pole in 2016. These ships and their Geological Survey of Canada-led scientific crews took part in the last of several joint international survey expeditions to the Arctic Ocean that advance the state of knowledge of this remote region, and secure geological and bathymetric data required by the United Nations in order to prepare the upcoming 2019 Arctic Ocean extended continental shelf submission by Canada under the United Nations Charter Law of the Sea, Article 76. (b) Some of the crew involved in this expedition. Photo credits: Asa Lindgen (a) and Lars Lehnert (b).

mapping and 3-D mapping, we will continue to make new investments in the application of artificial intelligence, geomodelling, and the wider uses of geoscience in tackling controversial environmental and societal problems. In working toward the implementation a new strategic plan (Fig. 10), we will engage with Canada's geoscience community to help address the issues of today and the many exciting challenges of tomorrow.

GSC Strategic Plan Priorities 2018-2023

Geoscience Knowledge for Canada's Onshore and Offshore Lands

- Publish new knowledge of Canada's geology in frontier areas of the Arctic onshore and offshore,
- Complete delineation of the outer limits of Canada's extended continental shelf in the Arctic, thus fostering international recognition of Canada's last frontier.
- Develop and implement new programs, tools and methods to discover, model, visualize and interpret the 3-D geology of Canada's lands

Geoscience for Sustainable Development

- Develop new mineral deposit models through research on how geological processes in ore-generating systems evolve through time. Support technological innovation within the exploration industry, with the combined aim of stimulating the discovery of new subsurface deposits.
- Advance research to combine knowledge of groundwater aquifers and their links with surface water systems to build integrated models of water systems for sound, comprehensive water management by the provinces and territories.
- Continue to deliver authoritative geoscience, including research on cumulative effects, to support land-use planning and environmentally sound resource development, both on land and in our coastal and offshore waters.
- Facilitate development of low-carbon energy sources, we will support the fledgling geothermal industry and other renewable energy industries to assess resource potential, enhance energy recoverability and support environmental assessments.
- Develop methodology to better characterize shale-hosted resources and transfer knowledge to industry, regulators and other stakeholders.

Geoscience for Keeping Canada Safe

- Develop advanced hazard models for earthquakes, tsunamis, landslides and space weather to support regular updates of building codes and emergency planning.
- Assess the impacts of climate change on the water cycle, permafrost, and coastal erosion and inundation to enable planning of resilient communities and infrastructure.
- Continue to work with the Canadian Hazard Information Service and Ocean Networks Canada to build an earthquake early warning system for southern British Columbia.
- Integrate our geoscience with socioeconomic analysis and engineering data to provide a comprehensive understanding of risk from natural hazards and climate change to critical infrastructure and urban centres.
- Focus on transferring this knowledge of hazards and risk to a wide range of stakeholders, including the provinces and territories, professional associations, and the insurance industry, to support actions that will decrease Canada's exposure to natural disaster and climate change.

Geoscience for Society

- Establish a modern publication process that incorporates open science principles and is responsive to client needs.
- Ensure that we have the infrastructure and processes needed to store, manage, analyze and openly share our data and knowledge products, work with provincial and territorial surveys to synthesize Canada's geoscience knowledge and data, and develop open and dynamic web portals to share geoscientific information.
- Initiate dialogue and relationship building with Federal-Provincial-Territorial counterparts, Indigenous groups and NGOs
- With Provinces-Territories, academia, and professional associations, investigate ways to build geoscience capacity within Indigenous communities to enhance the incorporation of geoscience knowledge into land management decision-making by communities

Our People, Our Science

- Support and develop a resilient, high-performing and diverse workforce skilled in emerging and traditional areas of geoscience research
- Rejuvenate our staff and acknowledge their continued efforts to advance public geoscience in Canada.
- Foster a modern work environment that balances sound scientific infrastructure and a healthy workplace, offers world class laboratories, collections and facilities and provides employees with opportunities to contribute meaningfully to the development of Canada.
- Serve as the hub of geoscience research in Canada, linking Provinces-Territories, academic and other government activities through collaborating with other federal departments, other levels of government, universities and international research institutes.
- Foster a culture of respectful relationships (across sectors, hierarchies, genders and nationalities) and contribute to all staff well-being and mental health

Figure 10. The main goals of the 2018–2023 Strategic Plan of the Geological Survey of Canada (Geological Survey of Canada 2018).

As the world changes around us, we will change with it; we will “skate to where the puck is going to be”, not where it is now. In the process we wish to develop partnerships with other leading scientific organizations in Canada to identify new areas where science can contribute to Canada’s economic, environmental and social well-being.

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GAC-MAC: FIELD GUIDE SUMMARY

Québec 2019: GAC–MAC–IAH Joint Annual Meeting Field Trips

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WHERE GEOSCIENCES CONVERGE

The Geological Association of Canada (GAC), the Mineralogical Association of Canada (MAC) and the Canadian National Chapter of the International Association of Hydrogeologists (IAH-CNC) invite geoscientists to their joint annual meeting in historic Quebec City, a UNESCO World-Heritage site. Participants will have the opportunity to visit and discover the warmth and charms of Quebec City and explore its many attractive natural sites, where converge three geological provinces: the Appalachians, the St. Lawrence Platform, and the Grenville. The conference's theme "Where Geosciences Converge" aspires to promote collaboration and stimulating discussion among geoscientists during symposia, special sessions, short courses and field trips, under the umbrella of four multidisciplinary themes:

- Geosystems and Hydrogeosystems
- Resources, Energy and Environment
- Geosciences and Society
- Big Data for Geosciences

For full details on the technical program, travel and accommodation information visit: *gacmac-quebec2019.ca*.

Nine field trips are offered, both before and after the meeting, from day-trips to multi-day far-reaching tours that cover a range of topics. The pre-meeting, one-day "*Upper Ordovician succession in the Quebec City area: transition from carbonate to clastic forelands*" field trip, organized by Denis Lavoie (GSC-Quebec), will address the changes of tectonic setting and paleo-oceanographic conditions at the margin of Laurentia during the Late Ordovician, when the rapidly foundering of the warm- to ultimately cool-water like carbonate ramp was succeeded by organic matter rich black shales and overlying flysch (Fig. 1). The field trip will examine the rapid facies, faunal and geochemical evolution of these sequences and the transition from the carbonate ramp to a deep, fine-grained clastic succession.

The one-day field trip entitled "*Champlain Sea deltas and the St-Narcisse Moraine in the Portneuf and Mauricie regions of southern Quebec: 3-D stratigraphic modeling and regional aquifer systems*", led by Michel Parent (GSC-Quebec) and colleagues, will be of particular interest to quaternary- and hydro-geologists, and set the table for multiple groundwater-related special sessions. West of Quebec, the Portneuf and Mauricie regions host some of the largest, most productive and widely used granular aquifers in southern Quebec. Over the last 20 years, these aquifer systems have been extensively investigated in a series of studies ranging from 3-D stratigraphic models to groundwater flow modelling. The field trip will introduce participants to the regional groundwater systems of this part of the Laurentian foothills

Figure 1. Panoramic view of the transition between the Precambrian gneisses, Ordovician carbonate and clastic foreland units, Montmorency Falls. Photo by S. Castonguay.

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Figure 2. Panoramic view of the reliefs associated with the three geological provinces in the Quebec City area. 1- Canadian Shield/Grenville province; 2- St. Lawrence Lowlands/Platform; 3- Appalachians. Photo modified from *Quebec City Tourism*.

and present the stratigraphy and architecture of the Late Quaternary sediments hosting these aquifer systems, most notably the large paleo-deltas deposited by meltwater-fed rivers along the northern margin of the Champlain Sea and the glacio-fluvial/marine sediment bodies associated with the Saint-Narcisse Moraine and emplaced below the Champlain Sea limit in the St. Lawrence Valley.

Located 125 km east of Quebec City, the Charlevoix impact structure will be visited during the one-day "*The Charlevoix impact structure and seismic zone*" field trip, co-led by Léopold Nadeau (GSC-Quebec, retired) and Gordon Osinski (University of Western Ontario) and will represent a field introduction to the special sessions on "*Impact cratering in the solar system"* and "*Terrestrial analogues for comparative planetary geology and astrobiology"*. This locality is among the largest at ~54 km in diameter, and the most accessible meteorite impact structure in eastern North America. The Charlevoix impact structure occurs at the heart of the Charlevoix Seismic Zone, the locus of the highest seismic hazard in continental eastern Canada. Since the arrival of the first Europeans in the early 1600s, the Charlevoix Seismic Zone has been subject to five earthquakes of magnitude 6 or larger. The Charlevoix impact structure gives the region its singular landscape, with its central uplift, Mont-des-Éboulements, which stands at 780 m above sea level, surrounded by the ~40 km-wide peripheral ring trough. The overall morphology of the structure matches that of complex impact craters. Shatter cones, injection breccias and shock-related planar deformation microstructures in quartz and feldspar crystals are widespread and provide compelling evidence for the extent of shock metamorphism.

Quebec City is located at the junction of three geological provinces, bestowing upon it a unique geological panorama, which includes a historical district that dates back to the first days of the colony. The field trip "*Québec, fortified City: Geological and Historical Heritage*" that Parks Canada colleagues and I lead is a relaxed short-day walking tour through the streets of Old Quebec that combines history and geology with a multidisciplinary perspective. Quebec is the only city in North America to have retained major parts of its original defence system. The 4.6-km-long fortifications are characterized by flanking and defence in depth, which represent more than just the vestiges of the military art of war, but also bear witness to the era of fortified cities between the 17th and 19th centuries. From Upper Town, standing on the "Promontory Nappe," which represents the frontal thrust sheet of the Appalachians in the area, one can see to the north, across Logan's Line, the lowlands of St. Lawrence Platform, and the billion year old but still mountainous roots of the Grenville Orogen, part of the Canadian Shield (Fig. 2).

Pierre Verpaelst (Canadian National Committee for Geoparks) and André Desrochers (University of Ottawa) invite participants to two post-meeting field trips that are companion to the special session on "*Geoheritage: from local to international*" and the short course on geoheritage. The first, three-day field trip will visit the "*Geoheritage of the Gaspe Peninsula: examples of the Percé UNESCO Global Geopark and the Miguasha World Heritage Site*" and explore the main elements of these two sites (Fig. 3). The second three-day field trip entitled "*Geoheritage in development: the Charlevoix Astrobleme and Saguenay Fjord Aspiring Geoparks*" will introduce participants to these future geoparks and expose the challenges faced by their promoters.

After the meeting and the special session on "*Ophiolites as markers of oceanic and orogenic settings*", a two-day field trip co-led by Jean Bédard (GSC-Quebec) and Alain Tremblay (University of Quebec at Montreal -UQAM) will head to Thetford Mines to contemplate "*The Thetford Mines ophiolite and its orogenic con-*

Figure 3. Rocher Percé, Quebec, part of the Percé UNESCO Global Geopark. Photo by S. Castonguay.

text". Participants will visit the critical localities of the stratigraphy and the structural characteristics of the ophiolite complex, with a particular emphasis on pre- to syn-obduction structures and associated lithological variations in the crustal section of the ophiolite, and its overlying sedimentary cover. The trip will visit major lithological facies constituting the ophiolite complex: mantle, plutonic crust, boninitic lavas and dykes, chromitites, and hydrothermal systems. The excursion will examine pre-obduction synmagmatic structures that are attributed to fore-arc seafloor spreading, syn-obduction structures and facies (dynamothermal aureole and sole, intra-mantle granitoids, piggy-back basin sediment), as well as post-obduction overprinting structures related to both the Salinic and Acadian orogenies.

Irregularities in the geometry of continental margins, such as promontories and re-entrants, act as major controls on sediment distribution throughout a Wilson cycle. Stratigraphic variations, both parallel and perpendicular to the margin, allow the identification of second- and third-order morphologic irregularities. This is the case for sedimentary assemblages comprising the thrust sheets adjacent to the Montmorency Promontory that Pierre A. Cousineau (University of Quebec at Chicoutimi -UQAC) and Hugues Longuépée (Champion Iron Ltd.) propose to visit during the one-day field trip entitled "*Impact of an irregular margin on the sedimentary evolution of a narrow shelf-slope environment (Quebec City area)*". The Cambro–Ordovican successions of the Appalachians in the Quebec City area attest of the transition from deep-sea turbidites to shelf-edge deposits formed during the rift-to-drift phase to the eustatic and tectonic instabilities of an Atlantic-type passive margin before the onset of the Taconic Orogeny. Sediment near Quebec City was deposited at the edge of a promontory with a narrow steep-sided, horst-and-graben shelf. In regional paleogeographical reconstructions, the platform widens to the southwest, and has a ramp geometry where a large fluvial system developed. To the northeast, major canyons cut through the shelf and fed directly deep-sea fans.

John M. Hanchar (Memorial University), Marian Lupulescu (New York State Museum), and Jeff Chiarenzelli (St. Lawrence University) invite participants to the Adirondack Mountains, in New York State, to explore the regional Grenville geology and to visit several spectacular exposures of magnetite-apatite (MtAp) deposits and their hydrothermally altered Lyon Mountain Granite host rocks during the three-day "*Magnetite-apatite (MtAp) deposits and related rocks in the Adirondack Mountains, New York State*" field trip, based out of Ticonderoga, NY. After an introduction to Adirondack Grenville geology, several classic outcrops (e.g. Woolen Mills, the historic Gore Mountain garnet deposit), historic MtAp mines and deposits and host rocks will be visited, including, amongst others, the Barton Hill Mine (Mineville), Rutgers Mine (Fig. 4), Skiff Mountain Mine, and Dannemora.

Figure 4. Magnetite-apatite-clinopyroxene segregation in Na–K- altered Lyon Mountain Granite host rock, Rutgers Mine; displaying possible evidence for magma mixing. Photo by J.M. Hanchar.

I hope this menu of field trips will appeal to the broad geoscientific community and that you will visit Quebec City for GAC-MAC-IAH 2019. See you next spring! Further information can be found at *gacmac-quebec2019.ca*.

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