Geological Survey of Canada 8.0: mapping the journey towards predictive geoscience

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Abstract: The Geological Survey of Canada (GSC) has been furthering the geoscientific understanding of Canada since its inception in 1842, the equivalent of seven generations ago. The evolution of the activities of the GSC over this period has been driven by evolving geographic, economic and political contexts and needs. Likewise, new technologies and evolving scientific methods and models shaped broadly the successive generations of GSC geoscience activities. The most recent GSC generation presented a mixed portfolio of large framework mapping geoscience programmes, and more targeted, hypothesis-driven geoscience research, and the development of decision support products for a range of government, industry and other stakeholders needs. Entering its eighth generation, the GSC and related organizations are embracing digital technologies for applications such as the evaluation of mineral resource potential, the evaluation of risks and the early warning of earthquakes. In order to do so, the GSC will need to develop new methods and systems in co-operation with other geological survey organizations, and target its data acquisition and research to further advance its ability to respond to the evolving needs of society to navigate geology through space and time, from the past to the present, and from the present to the future.

Supplementary material: Open data for the public funding of the Geological Survey of Canada can be found at: https://doi.org/10.6084/m9.figshare.c.4814589

Geological survey organizations (GSOs) share a number of common features. They are mandated, with a largely domestic focus, to perform geoscientific studies and related technical surveys and mapping to: (1) inform the management of national lands; (2) inform the development of natural resources; and (3) support the protection of people and infrastructure from natural and anthropogenic hazards such as landslides, earthquakes and nuclear waste.

Since its inception in 1842, the Geological Survey of Canada (GSC) has surveyed and researched the geology of Canada to support the development of the country’s lands and mineral resources. In the last 25 years, this development was increasingly complicated by changing domestic and international economic, social and environmental drivers and policies. In addition to being influenced by these drivers, the evolution of the GSC parallels changes that occurred in other GSOs, largely due to changing:

- technologies (industrial revolution (mechanization), second industrial revolution [mass production], digital revolution (computer and automation), Industry 4.0 (cyber physical systems));
- research and development (R&D) management models (e.g. R&D as ivory tower, business portfolio, integrative activity, networks; see Doern et al. 2016 for a good review of Canada’s science policy context); and
- geoscience partners and clients (e.g. national/international governments, industry, R&D centres, academia, associations, federal research centres, institutional funders, venture capitalists and Indigenous).

This paper first summarizes the evolving Canadian geographic, economic and political context in which the GSC itself evolved within a changing global socio-economic, policy and technological context. We show that the drivers of change and their expression in the particular Canadian context, have oriented the activities derived from the broad GSC mandate and the evolution of its mission of geoscience data gathering and knowledge delivery since its inception to the present. Second, we outline where we are today and how the GSC draws from foundational and targeted geological surveys to develop and orient hypothesis-driven research and provide practical information to support decision making by a range of government, industry and other stakeholders. Finally, we review the issues that the GSC faces today, and how the organization is adapting and orienting its future directions, in particular as it relates to the changing world of information technology and management (IT/IM).

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The Canadian context

Canada’s history and changing geographic and political context over the last two centuries have strongly influenced the demand for geoscience, shaped its federal, provincial and territorial GSOs and oriented their activities.

Canada is a polar country with a vast territory (Fig. 1). Its onshore expanse ranks second in the world with 10 million km² and includes an additional 7 million km² of offshore-submerged lands. Canada’s geology is complex, containing the world’s oldest rocks to the youngest sediments, and a rich endowment of mineral and petroleum resources. These unique national geological circumstances created a fertile ground for geological exploration and research, in synergy with evolving domestic and international demand (Lebel 2018). As a result, from the seventeenth to the twenty-first century, Canada’s rich endowment of natural resources and entrepreneurial culture has shaped it into a trading nation. This geography also comes with challenges: it is dominated by a cold climate that requires vast amounts of energy for heating and transportation.

As of 2018, Canada, with a total population of 35 million people (as of 2016 Census, Statistics Canada 2017), posts the largest population growth of G7 countries (at 1.4%, or double the USA, Statistics Canada 2018). Overall, it is one of the most sparsely populated countries in the world, with a density of

Fig. 1. Canada is an Arctic country with a rich indigenous heritage. More than half of the land surface of Canada is underlain by permafrost, either sporadic, discontinuous or continuous that is fast evolving (NRCan 2019). Most of the population lives in urban areas in the south. Canada’s land governance includes multiple jurisdictions: federal lands, 13 provinces and territories, and indigenous lands recognize 70 historic treaties signed before 1923. Since 1975, Canada has signed 25 additional treaties (called modern treaties or comprehensive land claim agreements) with Indigenous groups in Canada. Some of these treaties include self-government. These treaties have provided among other things indigenous ownership over 600 000 km² of land (almost the size of Manitoba), capital transfers, protection of traditional ways of life, access to resource development opportunities and participation in land and resources management decisions and certainty with respect to land rights in round 40% of Canada’s land mass, and associated self-government rights and political recognition (Crown-Indigenous Relations and Northern Affairs Canada 2018). Figure modified from Smith & Burgess (2004).
3.9 people/km². However, the Canadian population tends to gravitate around southern urban areas, where over 80% of them reside. The density of the three Canadian metropolises (Toronto, Montreal and Vancouver), ranging between 800 and 1000 people/km², contrast deeply with the sparse population density (<0.1 people/km²) of the three vast northern territories of Nunavut (NU), Yukon (YK) and Northwest Territories (NT) that represent together 40% of the national land base area (Fig. 1).

This enormous gap is a key geopolitical characteristic of Canada; that is reflected in the northern areas by an under-developed economy and a thin and dispersed infrastructure of road networks, harbours and energy production. This demographic reality also includes contrasting cultural and economic differences that dictate the contemporary dynamics of natural resource development. In particular, the sparse and resource rich north is more heavily populated by Indigenous people (e.g. NU: 85%; NT: 47%; YK: 21%, Statistics Canada 2017), while the dense and resource demanding south is dominated by non-Indigenous (95%), with an increasingly diverse population (one in five Canadians is now foreign-born according to the 2016 Census; Statistics Canada 2017). Many provinces have witnessed indigenous opposition to major resource development projects in the last few decades. As a result, new economic environments emerged, in which negotiation and benefit agreements for indigenous people had to be reached to enable the development. In Canada, geological surveys are often necessary to assess resource potential, when the conservation of land under indigenous claim or otherwise such as through proposed national parks or marine protected areas are being proposed.

Today, the natural resource sector remains an important share of Canada’s economy, tied chiefly to the growth of oil and gas development. Cumulatively, the energy, mining, metals and forestry sectors, were worth 17% of Canada’s GDP in 2017 (NRCan 2018a). Canada is also a global mining powerhouse. As outlined in the new Canadian Minerals and Metals Plan (Canada’s Mines Ministers 2019), our geological endowment and reputation are the envy of the world. Canadian leadership and expertise can be found at virtually every link along the mining value chain. Other countries look to Canada and Canadian companies for the way we build partnership with Indigenous Peoples, build relationships with local communities, and protect the environment. Canada is a top destination for exploration spending and offers unparalleled access to capital markets. We are innovative, and we have robust junior mineral exploration, clean technology, processing, and mining supply and services sectors.

In 2017, Canada was the top destination of the global mining exploration budget for the 16th consecutive year with 13.8% (US$1.1b) (S&P Global 2018). According to the annual Fraser Institute opinion survey of mining companies (Stedman & Green 2018), respondents have consistently indicated that, while 40% of their investment decision is determined by policy factors, 60% is based on their assessment of a jurisdiction’s mineral potential. The on-going production of public geoscience originating from GSOs remains a key factor to shape favourable mining investment opinions across Canada.

Canada’s economy is also supported by a strong and diverse energy sector. As outlined in the Energy Fact Book,

from an energy perspective, Canada is very fortunate. We have a large land mass, small population and one of the largest and most diverse supplies of energy in the world. Our rivers discharge close to 7% of the world’s renewable water – a tremendous source of hydroelectric power. We have the third-largest global supply of proven oil reserves and third-largest reserves of uranium; our energy resources are a source of strength that continues to shape our economy and society. Canada is at the forefront of innovative technologies for how we produce and use energy. (NRCan 2018b)

Canada is the world’s second largest producer of hydroelectricity and 81% of its electricity generation now comes from non-GHG emitting sources when other renewables and nuclear power are accounted for (National Energy Board 2017). Canada counts some 0.9 million km² of freshwater lakes and rivers, amounting to the largest volume of surface water on the Earth, but it is unevenly distributed and some 25% of people depend on groundwater for domestic water use, set in varying geological conditions.

Water and weather-related hazards have a large impact on Canada. The rural and urban populations of Canada experience climate change in different ways, and altogether with increased alarm, as severe, multi-billion dollar weather-driven natural disasters have impacted Canada in the last decades including the Montreal–Ottawa Ice storm, the major floods of the Red River, Saguenay watershed, Bow and Highwood Rivers (Calgary), Ottawa River (2017 and 2019) and the major wildfires of Alberta (e.g. Fort McMurray and others) and British Columbia.

Policy context

Canada’s economic wealth is derived from its people, a dynamic private sector and strong institutions. It has and still draws heavily on the development of its mineral and water natural resources’ advantages. These advantages come with a large burden of responsibility on all levels of Canadian government to understand, develop and manage responsibly these resources. This desire dictated the need for geological surveys, and created vast demand for data,
research and predictive tools to orient mineral, energy and water exploration and development. Science and monitoring have also been necessary to mitigate natural hazards such as earthquakes to increase public safety.

The GSC operates within the federal department of Natural Resources Canada, and co-provides public geoscience together with Canada’s 12 provincial and territorial geological surveys under the thrice-renewed ministerial level ‘Intergovernmental Geoscience Accord’ (IGA) that describes the respective roles and responsibilities of the federal and provincial/territorial geological surveys (Energy and Mines Ministers’ Conference 2017). Under the IGA, the GSC is responsible for providing Canada with a comprehensive geoscience knowledge base that contributes to economic development, public safety, and environmental protection. It does so by acquiring, interpreting and disseminating geoscience information concerning Canada’s landmass and the offshore. The GSC carries out geoscience programs that are typically thematically based and national in scope and significance. Unlike the provincial and territorial surveys, whose activities are geographically constrained to their own jurisdiction, the GSC operates in all provinces and territories. The GSC also carries out marine studies that are unique among the geological surveys, and has a leadership role in representing Canada in international geoscience activities.

Global modern socio-economic and technological context

Since 1985, the world has witnessed a period of rapid environmental and technological changes that have brought forward new questions for geoscience. Over the course of the last 30 years, the world has also witnessed enormous economic, social, technological, environmental and political changes. The changes experienced by humanity and nature over this period have no parallel in human history. The end of the Cold War, new world trade agreements and China’s economic reforms were major driving political factors. These factors combined with the rapid emergence and wide dissemination of digital technologies, including the internet, that drive what is called the Digital Revolution or Technological Revolution 3.0 (start date 1971, marked by the Intel 4004 microprocessor). Concurrent with these developments, various factors such as the ‘Green Revolution’ in agriculture (initiated in the 1960s) and trade globalization led to a period of economic prosperity that lifted billions of people out of extreme poverty (UN 2019). Yet this period also marked a period of rising global environment damage, and increased income inequalities across the world (Alvaredo et al. 2018). The increasing consumption of oil, combined with that of other fossil fuels, caused the world CO$_2$ emissions to rise from 20.8 Gt/yr in 1985 to 36 Gt/yr in 2014 (UNEP 2017). Global average temperatures, driven by the CO$_2$ concentration (IPCC 2014) increased by nearly 1°C since the 1970s. This trend continues unabated as global policy makers and governments struggle to find suitable and widely acceptable policies to bend this trend downward through emission reductions, as the scientific community, the United Nations and many other groups, including scientists, issue dire warnings and calls for changes to ensure a sustainable future for humanity (e.g. Ripple et al. 2019).

Evolution of the GSC

Since 1842, GSC science has responded to changing national needs (Zaslow 1975; Lebel 2018). Figure 2 illustrates the evolution of GSC’s political, science and technological drivers across the eight generations with a view to the future, the evolving national needs marked by an ‘S curve’ of overlapping and varying demands.

The history of the GSC can be divided into three main phases aligned with changing federal drivers and priorities that can be parsed roughly into shorter 25-year ‘generations’. These phases can be ascribed cycles of demand or need for GSC activities. We can separate: (1) the ‘Pioneer Phase’ c. 1842–1942 (Generation 1–4), marked by rapid growth focused on geological field surveys, with maps and related reports; (2) the post-war ‘Boom Phase’ of 1945–86 (Generation 5–6) of exponential growth in activities that incrementally added new research-oriented activities; and (3) the current ‘Contemporary Phase’ of activities from around 1986 to the present that introduced predictive studies and systems (Generation 7–8). The interplay of societal demand for the GSC activities is illustrated in Figure 2. The three historical phases of the GSC are also correlated with varying public funding resources compiled in Figure 3.

Pioneer Phase

Generation 1 represents the foundation phase of the GSC by an act of the legislature and the hiring of its first director William E. Logan in 1842 to ‘cause the geological survey of Canada’ (Alcock 1947). Financial, industrial and government interests converged and led to the creation of the GSC at a time when there was a need to find basic minerals. Coal, copper and other industrial minerals were especially needed to spur the industrial development in Canada in line with the benefits of the steam engine and other elements of the industrial revolution
(started in 1771, Revolution 1.0, see Fig. 2). Railroad development only started in earnest in Canada in 1850, 30 years later then in Britain (Revolution 1.5), but expanded very rapidly, with the Great Trunk Railway extending 800 km westward from Montreal, Quebec to Sarnia, Ontario in 1860, and the Canadian Pacific Railway expanding further reaching the Pacific Coast in 1885 (Wallace 1948).

**Fig. 2.** Eight generations of society-driven geoscience at the Geological Survey of Canada 1842 to present with a view to the future, as described in the text. This figure presents also the broad driving issues, the science methods (or paradigm shift such as Plate Tectonics), the enabling technologies and the geoscience programme orientation of activities for each generation. The timeline also includes the major industrial revolutions that have influenced the GSC generations. Figure inspired by the ‘S curve’ of business emergence and obsolescence of Nunes & Breene 2011.

**Fig. 3.** Public funding for the Geological Survey of Canada, 1842–2018, separated in three phases, compiled from public and internal reports (incomplete), converted to 2018 CAS. The open data is available in the supplementary material.
Generation 2 characterized by the expansion of the Canadian railroad network parallels the expansion of the Canadian territory in the nineteenth century and the desire of the government for western colonization and nation building. This drove the need for systematic land surveying, topographic and geological mapping (see Hamilton & Sebert 1996 for a detailed chronology). Broad reconnaissance-level surveys oriented organizational development in Canada’s provincial and federal governments. As an illustration of this government drive, in 1879 no less than ten field survey parties were sent to western Canada to find the best route for the transcontinental railroad and settling agricultural communities. Over this second generation, a steady stream of over 360 GSC reports and maps were published, detailing findings from the staff geological surveys, as well as the results of mining and petroleum exploration and development.

Technological Revolution 2.0 (1879, marked by Edison’s light bulb) led the transition toward Generation 3. The introduction of new industrial scale steel making technologies, concomitant with the introduction of the electrical generator and distribution grid led to another major industrial expansion, including major mining development accelerated by new technologies (i.e. diamond drilling, dynamite and railroads shipping). From a nascent stage over the course of the 1867–92 period, mining of metallic ore grew quickly from 1892 through the next 25 years. It was driven by the discovery of gold and other mineable ores in British Columbia, the next western ‘Gold Rush’ following California and western USA that started in the 1840s to the 1870s, and continued with the Yukon Klondike gold rush (YK joined Canada in 1898), and the discovery of rich nickel and copper deposits around Sudbury, Ontario in 1883 (Sudol 2004).

Support for the fast expansion of mining were at the core of Generation 4. The overall mineral production of Canada in 1917 reached CAS190m (in 1917 currency, a 2018 equivalent of CAS3.7b, Canada Department of Mines 1919), that is about 10% of the value that it would reach by 2017 (CAS45.3b, NRCan 2019). There was a growing world industrial appetite for minerals (for manufacturing and two world war demands), that continued through the 1930s economic depression with a specific demand for gold. The emergence of mining as an important economic sector in Canada created the steady demand for geoscience that has been maintained to this day, and was the main driver for focused geological surveying through Generation 3 and 4 and until the end of the Pioneer Phase of the GSC.

The use of geological mapping to support prospecting, combined with the advent of drilling and other mining technologies and the development of skilled labour worked synergistically to achieve a remarkable economic outcome. By the end of Generation 4 in 1942, Canada’s mineral production reached CAS567m (or CAS8.8b, 2018 equivalent) or twice as much as a generation before in 1917 (Canada Department of Mines 1945).

**Boom Phase**

The second phase of GSC development, the ‘Boom Phase’, started with WW2 and parallels the expansion of government spending and the development of a number of new science laboratories in Canada. These new investments benefited the GSC with a new laboratory facility on Booth Street in Ottawa in 1956 and several others in the regions involving GSC and other departments: the Bedford Institute of Oceanography, 1962; the Institute of Sedimentary and Petroleum Geology, Calgary, 1967; the Institute of Ocean Sciences, Sidney, 1977. This paralleled the expansion of university research, the highway network and general post-war economic expansion.

Technological Revolution 2.5 had initiated the Age of Oil, Automobile and Aeronautics (marked by the advent of the Ford Model T in 1908), and the fast-growing demand for petroleum and minerals that dominated and created a boom demand for geoscience through Generation 5 to 6. These new technologies also accelerated western and northern geological explorations, supported by new air photograph surveys. The steady mapping of the geology and minerals that had led the way to major discoveries and mineral development was foundational for the discovery of the major oil fields of Alberta and the development of gold, radium and uranium mines, and an oil field (Norman Wells, 1921) in the NT starting in the 1930s (Lord 1951). This also guided exploration to new discoveries by industry that occurred through Generation 5 and 6 (e.g. the Leduc reef discovery of 1949 by Imperial Oil).

The success of the Manhattan Project to build the first atomic bomb during WWII and the allied technologies such as the first digital computer (e.g. Dyson 2012) created a positive climate for government support for science ( spearheaded in the USA by Vannevar Bush), and major new injection of funds in various universities and government science organizations (Doern et al. 2016), including the GSC, through funding for research and scientific equipment. It is notable that there was a high demand for mineral and petroleum potential models by policy that drove GSC activities such as the ‘Operation September’ project, a crash ‘quantitative’ national assessment of mineral resources in 1972 and many other such projects that continued steadily during that period (Findlay 2010).

The Boom Period was marked by major advances that were derived from war activities (e.g. geomagnetic and marine acoustics for submarine
hunting, and other instrumentation). This in turn led to the scientific breakthroughs that laid the foundations of the Plate Tectonic Theory, the revolution in geoscience of the twentieth century. Plate Tectonics served as an impetus for a complete reconsideration of the geological knowledge acquired before 1970, and a new period of development of models and theory within the broad geoscience community and within the GSC.

Contemporary Phase: 1986 to today

The ‘Contemporary Phase’ of the GSC was influenced by the advent of digital (Technological Revolution 3.0) and starts in 1971 with the introduction of microcomputers, their wide distribution and connectivity to ever more powerful computing platforms, which provided the impetus for the development of predictive models and systems in government.

The Contemporary Phase of the GSC has also been strongly influenced by important domestic policy choices that coincided with a slowdown of government growth. The turning point was a period of high inflation, high interest rates and high unemployment that started in 1984 (Di Matteo 2017). This period led to a ballooning federal budget deficit that rose steadily in spite of repeated government fiscal measures to contain it, up until drastic measures were implemented in 1995 to dramatically reduce the size and role of the federal government, which resulted in a more than 50% decrease in the GSC resources from its peak in 1986 (Fig. 3).

Generation 7 of GSC activities were also set against a turbulent global context, outlined above, where governments worldwide were challenged to tackle complex issues and achieve social and political consensus. For Canada, this included sustaining economic growth and creating jobs while facing an important crisis of national unity that pitted regional economic growth and creating jobs against national interests. This national unity crisis drove a strong political desire for new departmental management efforts to market GSC’s role and expertise to the central government, showcasing scientific applications to address policy issues and to respond to the needs of government and society.

In Canada, the first steps of major government change materialized itself through reductions in the size of the federal government and a rebalancing of the government role with that of the lower levels of governments. These reductions were absorbed through productivity gains (e.g. computing), increasing collaborations and a general reconsideration to focus on core activities relevant to the federal government. It also oriented and renewed senior
northern operations until GEM started in 2003. Nonetheless, the pre-GEM early mapping supported the undertaking of more detailed regional mapping by the new Canadian Territorial surveys in NT, NU and YK and vigorous prospecting that led to the discovery of major diamond mines in NT in the 1990’s. Although the Generation 7 GEM field campaign was broadly regional, it had to be targeted to areas of highest potential for applied knowledge progress for surficial, bedrock and geophysical surveys. The programme also ran synergistically with the GSC UNCLOS programme, to integrate data and knowledge and to achieve major advances in understanding, so as to bridge geology between the Arctic Islands and Canada’s offshore extended continental shelf. Traditional mapping methods and earth observation technologies will continue to be needed to advance geoscience knowledge and require efforts and funding to the Canadian GSOs for the foreseeable future, especially in order to predict cumulative effects, find economic resources and adapt to the impact of accelerated climate change already observed in northern Canada.

A policy push to achieve the difficult sustainability balance has continued since the Rio Summit of 1992 and sets the background against which the GSC evolved and contributed to the advancement of various environmental objectives that took the shape of groundwater, environmental and public safety geoscience programme activities during Generation 7. Technological Revolution 4.0 (2011, marked by IBM’s Watson victory on the US TV show Jeopardy) marks the beginning of the Artificial and Robotics Revolution whose future path remains uncertain and is based on the enormous science and technological advances that continued uninterrupted through Generation 7, and into where the GSC and the world are today.

The GSC today, reaching into the future

Generation 8 will most probably be driven by the need for sustainability in the context of global climate and environmental changes as well as by the growing influence of artificial intelligence (AI), as well as the changing needs of Canadians to mitigate climate change and adapt to it, especially in Arctic Canada. Another emerging policy need is the requirement for mineral resource assessments, to
respond to critical mineral demand in North America, and in response to the increased demand for batteries for e-vehicles (Reuters 2019).

Advances in robotics, computing and communication systems have opened the door to a world where vast quantities of data are generated and shared instantly. The use of this ‘big data’ is still in its infancy but provides new opportunities to understand the physical environment around us. Paradoxically, it also creates a world where there are blurred boundaries between real information and fabricated information, between objective evidence and ideologically derived pseudo-facts and between certainty and uncertainty. Both the uncertainties of how development projects will affect the future of people and the environment and the polarization of the public through political and media opinion drive the perception of risk and represent major challenges.

The GSC has a formidable mandate, ‘to make a full and scientific examination and survey of the geological structure and mineralogy of Canada’ (RATS Act, Minister of Justice 1985). Building on its history, this mandate has to be regularly actualized to focus the examination of the vast territory and to have impactful findings that bear applications to national issues that Canada faces today.

The Geological Survey of Canada Strategic Plan 2018–23 (GSC 2018) outlines the latest direction to maintain the relevance of the organization and to modernize its mandate (Fig. 8). The Plan responds to the public demand for social consensus in resource development. It states that it is unacceptable to exploit natural resources without regard to the environment and the people who live and work in the area. It recognizes the importance of urbanization, and the need to mitigate climate change and natural disasters. It confirms the important role that GSC research plays in addressing the global challenge of supply of mineral and energy resources in an environmentally sustainable way. It recognizes that technology is also changing our world and the influence that it has in shaping public opinion, policies and decisions about development projects. Emerging from this latest strategic plan is also the desire to get broader dissemination of geoscience knowledge to non-traditional and non-familiar users of geoscience maps and other knowledge products.

From surveys to systems: the evolving geological survey role

Recent technological advances and a federal policy commitment to Open Science are rapidly transforming GSC data collection/storage/user, modelling and decision support activities. GSC activities have
The ratification of the United Nations Charter Law of the Sea (UNCLOS) by Canada in 2003 has driven a large and joint GSC geoscience and Canadian Hydrographic Service bathymetric survey programme to delineate its extended continental shelf and make two submissions to the United Nations for consideration. The programme is an example of the GSC surveying a large territory in complex conditions. It has surveyed some 2.4 million km² of the seabed in the Atlantic and Arctic oceans that is claimable, non-overlapping extended continental shelf under the UNCLOS. The Arctic surveys alone completed in 2016 included 90 000 line km of multibeam bathymetric, sub-bottom profiler and shipborne gravimetric data, 18 000 line km of seismic reflection data, 8000 line kilometres of refraction profiling data, 800 000 km² of aero-gravity and aero-magnetic data, 800 kg of rock samples and three piston cores. The seismic and bathymetric surveys required the use of several icebreakers over a decade of activities. The pictures represent the cover pages of the publicly available Executive Summaries for the extensively documented Partial Submissions of Canada for (a) the Atlantic Ocean (Government of Canada 2013).
high level of co-operation with the provincial and territorial level of government, as well as with academia, industry and other national and international organizations. A modernization of GSC’s information management and communication practices with clients and stakeholders has become imperative in the current fast changing societal and technological environment. Data, models, knowledge and tools represent vast modern challenges for geological surveys and new opportunities for societal applications.

A major emerging challenge is to modernize the approach to acquiring and managing data, focus some efforts on the development of appropriate decision-support tools and solutions that are accessible to stakeholders on the range of issues that touches on the GSC mandate.

Three principal roles capture the range of modern GSC geoscience activities: producing data and information, carrying out research to produce knowledge and producing tools and systems to predict, alert or reduce risks. As outlined in Figure 9 these information-based roles tie with three spatio-temporal scientific functions:

1. survey the present state of the national land geology in 3D: map, analyse and build databases to describe and inventory the nature and relationships between geological features and properties such as the rocks, structures, minerals; groundwater, fossil and geothermal energy, geophysics, geohazards, etc.

2. establish the past geological history: models toward an understanding (of origin, age,
interrelationships between rock bodies, ore systems, ancient life, geohazards, etc.), within the overall Earth evolution context; and (3) establish future possibilities, risks and mitigation strategies: potential estimates of specific mineral resource discoveries over specific areas; assessments of vulnerabilities of people and infrastructures to natural hazards or of groundwater to contamination, scarcity and stewardship.

Over time, there has been an evolution from 2D to 3D geological mapping to the advancement of research to derive models and understanding of the Earth. Such research-oriented studies have advanced the general understanding of geological and other Earth surface processes, built on foundational maps and databases. This understanding in turn provides the foundation to develop predictive models about the location of resources and state changes in the Earth systems and the environment. Ultimately, 4D

**GSC Strategic Plan Priorities 2018-2023**

- **Geoscience Knowledge for Canada’s Onshore and Offshore Lands**: Largely focuses on hypothesis-driven research about mineral, energy and groundwater resources. Development of predictive tools, models, and technologies to find mineral resources and aquifers (i.e., groundwater and contaminant circulation; shale petroleum resources and induced seismicity).

- **Geoscience for Sustainable Development**: Focuses on the mitigation of natural hazards (including current climate change impacts). Mapping and observing natural hazards in real time, especially seafloor geohazards, micro-earthquakes, and space weather.

- **Geoscience for Keeping Canada Safe**: Capturing data and knowledge about the state of geology using broad scale onshore and offshore mapping, including big data acquisition. Supporting land planners, economic development, and fulfill government level knowledge requirements.

- **Geoscience for Society**: Broad data and knowledge translation and dissemination from GSC to society via easily usable products. Includes how to combine traditional and scientific evidence in land-use decision making in a context of reconciliation and nation-to-nation dialogues with Indigenous population.

- **Our People, Our Science**: Support, develop and renew a resilient and talented workforce. 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, 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.
predictive models, decision-support tools and alerting systems have emerged in the more recent past to guide the mineral and energy exploration, monitor and mitigate natural hazards and climate change, and manage or protect groundwater resources. Figure 9 illustrates this geological survey activity cycle continuum.

GSC data, knowledge-derived models and predictive tools have in-turn emerged as fundamental, spatio-temporal geological survey activities and tools, benefiting from scientific and technological advancements, and serve to address changing societal needs outlined above. Data, models, knowledge and tools represent vast modern challenges for geological surveys and new opportunities for societal applications. Figure 10 provides a view of the evolution and range of different information products and systems through history that underpin geological survey work and are described in more detail below.

**Geoscience surveys and synthetic views.** The first classic function of geological surveys is to describe the present, as derived from observation and synthetic views (Fig. 9). These are typically obtained from a range of surveys such as basic field work, airborne geophysics, Earth observation, laboratory and monitoring instruments, etc. The information captured by such surveys consists of a large series of datasets, including data, maps and related reports. This ranges from the original geological reports
and maps produced tediously on printed paper from the 1840s to the 1990s, now fully digital and distributed openly. The original geological maps and reports were later joined in this category by other datasets and knowledge products that generally map the present state of geology, and consist of big volumes of data derived from instrumental or direct observations, most often represented by geological, geophysical and other maps and related reports. Many new GSC maps and reports have emerged through time, the latest being derived through the benefit of new geophysical and satellite instrument platforms that have supported the probing of the surface and subsurface in applications such as maps of aquifers, the seabed and other geological features in 3D. Far from reaching an end, the mapping and monitoring of Canada’s geology has grown in diversity and created a growing appetite for ‘Open Data’ from government, industry and academia that continues today.

Observations about the present shape, structure, composition, thermal state and other characteristics of the Canadian landmass have continued to grow steadily as described above and have added incrementally new types of geoscience activities and studies. From the geological surveys and maps started in 1842, grew seismological and geomagnetic monitoring in the 1920s, followed by airborne aeromagnetic and other geophysical surveys in the 1950s, reconnaissance regional geochemical surveys started in the 1970s, and deep-probing lithospheric surveys under the LITHOPROBE programme in the 1980s and 1990s. The latest large bedrock and surficial mapping efforts are represented by the northern-oriented Geomapping for Energy and Minerals Program outlined above. Monitoring of the state of the glaciers and permafrost started in the 1960s, and new technologies provided the impetus for seabed mapping in the 1990s. Space weather monitoring came about in the 1990s as a response to major electric blackouts induced by geomagnetic perturbations related to solar storms.

Geoscience research for models and integration.

The modern orientation of the GSC toward basic and applied research, initiated in the Boom Phase led to new research-oriented activities that continued and accelerated in the Contemporary Phase of the GSC. This research led to the creation of new information products fundamentally different than the classic maps and reports that were typical of the Pioneer Phase (Fig. 2). As outlined in Figure 10, these new information products are the outputs of scientific research as applied to resolve fundamental geological questions. Example questions include how do mineral deposit form, how do groundwater contaminants migrate into aquifers, how do permafrost form, melt and interface with natural contaminants, how could we capture CO2 in underground reservoirs, what are the processes that drive the geographic distribution of earthquakes?

Most of the questions pursued through such research aim to understand earth processes that occurred in the past and may persist to the present. The knowledge outputs consist of scientific products such as peer-reviewed journal papers and other publications such as GSC Open file products that report on the pursuit of hypothesis-driven analyses, models and theories derived from the integration of basic data and knowledge.

Predictive geoscience and systems. The applied and basic geoscience research that is done upstream flows downstream into a function of predictive geoscience and systems. By understanding the processes that drive earth systems, geoscientists can develop products aimed at solving complex societal challenges. Products include predictive models, information and systems about vulnerabilities and risk of natural hazard events, as well as predictive maps of mineral potential to support land use planning, to balance decisions between the protection of biodiversity and ecosystems, with those aimed at stimulating economic activities in high potential areas.

The combination of the advent of research in geological surveys, a fast expanding suite of datasets, and the advancement of geoscience computing in the 1980s have been the impetus for the gradual development of mineral and energy resource potential assessments, one of the earliest forms of geoscience predictive tool. These models, which are still very much in development, have been succeeded by new tools, which in contrast draw directly from high-volume data stream observing instruments. These predictive tools are based on fundamental scientific and technological advances in geoscience, informatics and communication.

An example of such predictive geoscience products includes the space weather forecasting system implemented and perfected by the GSC starting in the 2000s, drawing from geomagnetic and solar flare observations (e.g. http://www.spaceweather.ca). More recently, the Canadian government has announced the development of earthquake early warning systems to protect people and infrastructure that will automatically alert the public and private sectors of fast approaching powerful seismic waves without the need for human intervention. This system will build on such systems developed in Japan and in the USA and on Canada’s pre-existing seismic monitoring system (Earthquakes Canada: http://www.seismo.ca), which satisfies the first function of ‘Geoscience surveys and synthetic views’.
Need for supporting IT/IM. The three broad functions and products of the GSC outlined in Figure 10, form an increasingly complex set of data, knowledge and tools that are supported today by a diverse set of digital and other technologies. Each set of functions and products present different IT and IM challenges.

Information related to the ‘Geoscience surveys and synthetic views’ function requires data servers that can host, serve and secure large volumes of data (‘big data’). Users demand readily available data that can be integrated seamlessly into GIS and other software. Increasingly, this big data requires sophisticated software to visualize and analyse in 2D and 3D. Among many challenges for geological surveys, lies in ensuring the quality the categorization of varied datasets using metadata. These data can range from semantically simple to requiring very complex and codified data structure in order to become interoperable between applications and systems (e.g. Brodaric et al. 2018). Taken together these diverse datasets represent thick data difficult to analyse through automated systems.

The ‘Geoscience research for models and integration’ function requires big data IT/IM solutions available from the first function, but also generates vast amounts of varied small datasets most often associated with particular hypothesis-driven analyses. Such analyses derive small datasets and are most often published as part of scientific journal papers or open files. Geoscientists thrive on multiple ‘Science Apps’ that help them process and visualize and project data (e.g. geophysical workstations), do specialized geostatistical analysis, or automate the probing of minerals through sophisticated geochemistry instruments. This requires a high variety of instruments and logging systems often not well integrated together. The IT/IM needs of research geoscientists often grow organically with their instruments. In the GSC, an emerging application is to robotize systematic elemental measurements of the geochemistry of minerals along a regular microscopic instrument grid, and to use AI to extract relationships through pattern recognition.

A new challenge for geological surveys is to navigate through the expanding array of instruments and data, and come up with appropriate support systems for the conduct of such research, from the selection of new instruments, growing of scientific
and technical skills, to generate new applicable and authoritative knowledge. Machine learning is a fast expanding field which is promising to address numerous inherent geoscience and related challenges such as ambiguous boundaries, spatio-temporal structure, high dimensionality, heterogeneity in space and time, and rare events, as outlined in Karpatne et al. (2018).

The ‘Predictive geoscience and systems’ function requires an even wider range of IT/IM solutions. At their simplest, they require combinations of layers of information in 2D or 3D, or the use of calculations using statistical or other approaches. A more advanced technique called remote predictive mapping (RPM) was developed by the GSC for mapping Canada’s north (Schetselaar et al. 2007), to predict spatial rather than temporal geoscience properties. RPM was used by several GSC scientists as an integral part of the geological mapping process designed to involve compilation, and re-compilation of data derived from existing geological maps, aerial photographs, satellite imagery and airborne geo-physical data. An RPM map, produced without collection of new, field-based data, may also serve as a first-order geologic map in areas where field-based studies cannot be accomplished due to expense of field access or remoteness. This predictive map is then used to guide mapping on the ground.

Along a spectrum of machine-based approaches that includes RPM, AI emerges as a solution to characterize objects and events from pattern mining techniques applied to spatio-temporal properties, estimating geoscience variables from observations, and a number of emerging machine learning methods (Desharmais et al. 2017; Karpatne et al. 2018). Several GSC scientists are already embracing AI for various practical applications to extract the relationships between large volume, highly dimensional datasets. A recent example in the GSC is to use AI to extract relationships through pattern recognition from data-heavy, robotized systematic elemental measurements of the geochemistry of minerals along a regular grid on a mineral grain in a laboratory-probing instrument. A new project involves the use of machine learning to build a content database of the some 83 000 publications currently available in the Geoscan database of GSC authored publications, using optical character recognition and pattern of text and maps. It is thought that this database will find multiple AI applications in the future to address complex questions about Canada’s geology. A future project currently being investigated would be to extract possible ore-bearing lithologies and structures from 3D seismic data volumes, to evaluate mineral potential at depth, using machine learning of example mining camps.

At the other end of the spectrum, alerting systems can be described as a type of prediction system only effective in a very small temporal window of seconds to minutes, with very long waiting periods between event warnings. It serves to alert the public and infrastructure managers of impeding natural disasters if new mitigation measures are taken, such as stopping trains or taking cover. An earthquake early warning system is such an alerting system, issuing warnings in near real-time as an event unfolds. It requires complex IT architectures, high-speed communication and fast computing solutions. Communication latencies of microseconds between various devices can cumulate and greatly reduce the effectiveness of earthquake early warning systems (Kuyuk et al. 2014). They have to be integrated with other public-alerting systems in order to be effective, and accepted by the stakeholders in a closely coordinated way. Developing such a system requires IT, scientific, policy, social and engineering expertise and goes far beyond the traditional realm of geological surveys; yet, it exemplifies the potential ramifications of GSOs’ outputs.

Planning for the future

The GSC has been considered by the federal government to be part of a national cluster of scientific laboratories that will succeed aging facilities distributed in Canada. This new cluster would provide an exciting new opportunity to integrate geoscience with other fields of science and engineering, and would be geared toward sustainable development. The GSC will have the opportunity to form new teams with other science organizations in this cluster and to reach nationally with other organizations. It is also a unique opportunity for partnering internationally with other GSOs and to address the enormous challenges of the twenty-first century to balance economic and societal development, with the protection of human health and the environment on Planet Earth.

This opportunity will also be the impetus for many new exciting directions to work with non-traditional scientific partners. The landscape for resource development in Canada is changing rapidly. Drawing on open data and modern GIS tools, non-governmental organizations are now able to develop detailed national-level maps to support their mandate (e.g. protection of biodiversity for World Wildlife Canada 2019), that can have a major impact on government policy. In contrast, this was inconceivable to government only a decade ago. Indigenous and non-Indigenous communities alike are interested in the cumulative effects that new development projects on land and water may have (Groulx et al. 2017). Integrated land-use planning is becoming an unavoidable method to achieve social consensus prior to reaching major development decisions. As the federal government and other levels of jurisdiction reconsider their approach to making decisions
for resource development, so too must the GSC think about how to support integrated land-use planning, including how to involve communities in the development of new data, research and predictive tools.

The GSC is a national provider of information on both land (surficial and solid geology) and water, including the integration of surface water and groundwater into the complete water cycle. The users for such information have become increasingly diverse and now include other agencies at all levels of government, Indigenous nations, professional clients such as engineers and planners, advocacy groups and the general public. In the coming years, we will seek new ways to both compile the technical information into a useable format and to disseminate it effectively. The GSC recognizes that this area of endeavour involves inherent complexities and that our goals in this area will be, to some degree, aspirational. However, we will investigate new ways of planning our programmes, undertaking our fieldwork, interacting with key stakeholders, and communicating our expert knowledge in ways that contribute positively to decision making related to natural resource development.

Conclusion

Much can be observed from the recorded history of the GSC through its general reports, public records, and from historical accounts such as those of Zaslow (1975), Blackadar (1976), Daschuk (1991), Findlay (2010) and Duke (2015). These accounts show that the GSC has continuously aspired to stay relevant to policy needs, while focused on the ambitious science mission that it was vested with. To be successful in a changing political and societal environment the GSC had to change and adapt, to address economic, environmental and public safety issues in Canada. In order to do so, the GSC leadership had to regularly ask itself what were the emerging needs of its clients (the government and citizens of Canada), work with its staff and stakeholders to focus its geoscience activities, and make appropriate investments in emerging technologies and expertise.

The challenge of the GSC has always been to remain relevant to the federal government and the citizens of Canada. At a few times, the GSC had difficulties to keep up with the changing socio-political climate and greatly diminished in standing. This materialized in its inability to secure incremental budgetary or human resources, which in turn hampered its ability to adopt new technologies and effectively deliver on its mandate. At other times, new activities blossomed in such a way that new organizations were split off and diverged away from the GSC, and grew on their own, such as the Canada’s Museum of Nature and the Canada Centre for Mapping and Earth Observation. Like all public service functions, the GSC has adjusted through time and with the times.

The informatics revolution and the rising AI and robotics revolution form the latest challenge and opportunity in a long series of technological advancements that have supported the growth of GSOs’ activities. In order to succeed in our fast-evolving world, GSOs will need to work together to master technologies, accelerate learning and share expertise. They will also need to work with engineers, IT/IM, other levels of government, the private sector and academia. The AI and robotics revolution promises enormous impacts on the efficiency of industrial production (at the possible expense of jobs), advanced financial services and clean low-carbon technologies. This might in turn increase the pace of progress in science, and in particular geoscience.

Emerging over the last two decades are increasingly sophisticated quantified models of the Earth’s atmosphere, hydrosphere, geosphere and oceans. The challenge ahead for science organizations such as the GSC will be to translate such sophisticated models into practical terms and to foster informed public debate on policy and societal issues of today and tomorrow.

The world is rich with human talent, as well as natural and economic resources that lends one to be an optimist about the future. Yet humanity is pressed to change rapidly in many ways to reduce vulnerabilities and critical risks to itself and the environment. The United Nations and UNESCO have adopted a number of aspirational frameworks, conventions and related goals and plans for sustainability, ratified or endorsed by Canada and most other nations: the Millennium Development Goals, the UNFCC, the Convention on Biodiversity, the United Nations Declaration on the Rights of Indigenous Peoples, the International Union of Geological Sciences ‘Resourcing Future Generations’ and ‘Deep Digital Earth’ initiatives. As we look to the future, it behoves like-minded GSOs to find partners and supporters to contribute to the advancement of these plans and goals, with their unique roles and capabilities as scientific organizations, integrators of knowledge, geospatial and temporal explorers, and convenors of collaboration and partnership to reach increased impact for the public good across a wide span of modern societies, and to solve pressing domestic and global policy issues for the current and future generations.

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The Geology of Canada was not only Logan’s magnum opus, but arguably the pinnacle of Canadian scientific publishing in the nineteenth century. If it was the peak, though, it did not mark the end of the Geological Survey of Canada and its publications. Contrary to the expectations of the provincial government in 1842, and to the experiences of the American state surveys, the GSC eventually became a permanent institution. This unlikely achievement has often been seen as Logan’s surpassing accomplishment in his role as Survey Director, and has been attributed to his ability to convince both ordinary Canadians and politicians of the value of the Survey’s work. But how exactly was he able to do this? The main challenge that Logan faced in educating Canadians about their geology was in making the rocks of their country ‘visible’ to them. In addition to his maps, and his acclaimed international exhibits, it seems to me that print was a crucial tool in Logan’s campaign to uncover the scientific and economic secrets that lay buried in the Canadian wilderness. The system of annual reports, which he initially dreaded and even considered a hindrance to his work, ultimately turned out to be one of his most powerful instruments in this task. By describing separately the geological, topographical, and economic features of the landscape, Logan was able to display to Canadians the past, present, and future of their land.

There lies the staying value and role of the geological surveys.

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