The changing role of Geological Surveys: introduction

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Abstract: This volume is a collection of papers authored by senior managers and heads of Geological Survey organizations (GSOs) from around the world in an attempt to provide a benchmark on how GSOs are responding to national and international needs in a rapidly changing world. GSOs face an uncertain future and need to understand global trends. Whereas population trends are somewhat predictable, societal responses to change are much less so and technological change is fundamentally disruptive and chaotic. As countries adopt sustainable development principles and the public becomes increasingly (but not necessarily reliably) informed about environmental issues using social media, the integration of resource development and environmental stewardship becomes increasingly important. GSOs will continue to provide key information about Earth systems, natural hazards and climate change in this context. This introduction comprises a short review of the global trends affecting GSOs, a snapshot of the state of GSOs, examples of how GSOs are adapting their activities to the modern world, including the growing use of big data, and an examination of international collaboration between GSOs. The time is perhaps ripe to reinforce international collaborations through a global network of GSOs. To achieve this will require leadership and a focus on the big picture of global sustainability.

Geological Survey organizations (GSOs) have been in existence in many countries of the world for over 100 years. Today, they have broad mandates: to map the country or state's geology, and conduct assessments of the resource potential for metallic and industrial minerals, fossil fuels and aggregate; to understand and mitigate geological hazards ('geohazards'), climate and environmental change; to provide data and knowledge on water and soils for land use planning; and to manage surface and groundwater resources. As countries adopt sustainable development principles and the public becomes increasingly (but not necessarily reliably) informed about environmental and land/marine use planning issues through education and social media, the integration of resource development and environmental stewardship becomes increasingly important. These issues require geoscience organizations to conduct integrated geoscience programmes and communicate results to a broad array of stakeholders including municipal governments, Indigenous peoples and other stakeholders to inform land-use planning and environmental decision-making.

The GSOs of the world have varying priorities, from frontier exploration to urban issues. As they seek to provide the comprehensive and consistent information needed to support management, modelling, and research, all strive to select appropriate resolution levels, formats, and methods. As in other spheres of scientific activities, geoscience-surveying technologies have greatly progressed and keep broadening the spectrum of instruments for field, remote sensing, borehole/*in situ*/laboratory data acquisition and computerized analysis. All GSOs

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seek an appropriate mix of activities to meet their stakeholder needs, ranging from collections and databases, 2D and 3D (and now 4D) geological mapp ing, geophysical and geochemical surveys, to programmes targeted towards energy, minerals and water, as well as hazards, environmental protection and restoration, public health, and engineering – while contributing to research that supports their survey roles.

The World Economic Forum's report (2016), 'Blueprints for a Greener Footprint', called for a rethink of how countries manage resource development: 'Achieving sustainable development requires explicit recognition that economic development and the environment can no longer be considered in separate spheres. Development is part of, and dependent on, the life-support systems provided by a stable and resilient environment'. The report called for planning at the landscape (or watershed) scale before making major project investments, requiring the development of an integrated knowledge base of the landscape, its resources and functions, which are critical to its long-term health and sustainability. Many GSOs are contributing to the shifting of the resource development paradigm, playing a dual role of being 'exploration enablers' and 'information providers' to a wide and diverse set of clients.

Increasingly, international agreements and goals to support the reduction of inequalities between more- and less-developed nations involve exchange of capabilities between nations rather than transfer of funds. Sustainable development on a global scale requires a domestication of complex global objectives, such as those of the United Nations Sustainable Development Goals (Gill 2016) and the UN Framework Convention on Climate Change (Nicholas 2014), that can only be achieved with whole of society support. GSOs are major contributors to this progress through their role as nationally and internationally linked science organizations, convenors of collaborations and instruments of public policy through their mandated responsibilities.

In a world where technology is rapidly evolving and information is available through smartphones, many GSOs report significant changes in government policies, mandates and operating environments in their contributions to this volume. It is therefore timely to examine how GSOs are both responding and contributing to the sweeping technological changes and globalization of ideas. There have been attempts in the past to assemble GSOs from around the world to review directions and evaluate the need for greater collaboration between them. This volume represents an update on this theme some 25 years after the initial effort (Bouchard *et al.* 1992). Senior managers and heads of GSOs from around the world were invited to submit papers providing their perspectives on the past, present and future of their GSO. The papers have been edited with a light touch in order to preserve the distinct perspectives that different countries bring to the global Earth sciences endeavour. We are conscious that this volume represents only a sampling of the GSOs around the world and that there are many perspectives that are not represented here. Nevertheless, we hope that the volume will serve as a benchmark on the response of GSOs to national and international needs in a rapidly changing world.

Global trends

GSOs around the globe face an uncertain future. Understanding global trends and envisioning how GSOs will have to respond to a rapidly changing present and an uncertain future world are important. Whereas population trends are somewhat predictable, societal responses to change are much less so and technological change is fundamentally disruptive and chaotic. Nevertheless, it is a challenge that GSOs must meet to survive and prosper in this moment of history.

In this volume, **Smelror (2020)** presents an extensive review of global megatrends from a GSO perspective. Despite projections that indicate stabilization of global population, economic growth is likely to continue over the twenty-first century, leading to increased use of natural resources. At the same time, the demand for particular metals such as cobalt, lithium and neodymium, used in key technologies such as batteries and electronics, will potentially unbalance markets and stimulate innovation for finding new mineral deposits or extract them from less economic deposits. The paradigm shift associated with transitioning from fossil fuel- to renewable energy- based economies will be potentially disruptive for GSOs, which have large coal or oil and gas divisions. The trend towards increased urbanization of global populations is also predictable and has implications for land and groundwater use.

At the same time, the planet faces significant environmental degradation, not least of which is that resulting from climate change (**Lebel 2020; Smelror 2020**). These issues are often framed, both locally and globally, in emergency management terms. In reality, they are 'wicked' problems to solve, resistant to quick fixes and requiring integrated understanding to support social and political decision-making. **Ludden (2020)** argues that whereas fundamental research on big planetary science is still necessary, the environmental and sustainability problems faced by the planet require GSOs to shift from identifying the problems to finding solutions. This implies deeper entrenchment of Earth system monitoring technologies and integrated data management.

Lebel (2020), in tracing the evolution of the Geological Survey of Canada through seven generations of national and global trends, shows how this evolution has been shaped by three factors: policy relevance, enabling technology and the scientific methods of the time. In the next 25 years, he points to sustainability as the key policy driver and the need for GSOs to develop capacity for predictive geoscience, comprising massive data integration and modelling of Earth processes, all the while keeping in mind the social context. The global trend towards increased computing power and the use of artificial intelligence systems to manipulate big data and model Earth systems will make this possible and many GSOs are building capacity in this area.

Watzel (2019) points out that the United Nations Sustainable Development Goals (SDGs) provide a framework for national government commitments and action on sustainability. Consequently, the German Federal Institute for Geosciences and Natural Resources (BGR) has aligned its activities with the SDGs under a guiding theme of Sustainability, Responsibility and Safety. The SDGs also inspire BGR's international cooperation programme. Similarly, the Sendai Framework on Disaster Risk Reduction provides a basis for adopting a risk-based approach to mitigating the effects of natural hazards in countries such as Malaysia (**Azizi *et al.* 2019**).

As coastal nations resolve their offshore territorial claims under the United Nations Convention on the Law of the Sea, and climate change opens Polar shipping lanes, their GSOs face extensive new frontier areas for geoscientific mapping and research (**Thorsnes *et al.* 2020; Verbruggen *et al.* 2020**). Despite significant advances in technology that allow detailed mapping of ocean floor relief and sub-bottom geology, the areas that require mapping are often vast and it is a challenge to find sustained funding to undertake this on a systematic basis. Geological Survey Ireland was successful in convincing the Irish government through a cost–benefit analysis that demonstrated an economic return of at least four times the investment across all sectors (**Verbruggen *et al.* 2020**). Recognizing this cross-sectoral economic benefit, as well as societal benefits, is important. Globally, there has been considerable effort to identify areas of the seafloor that need protection for fish and shellfish habitat, leading to the development of extensive networks of Marine Protected Areas and Conservation Areas. Using this movement towards marine spatial planning and sustainable use of marine resources was also key to funding of Norway's extensive seafloor mapping programme (**Thorsnes *et al.* 2020**). Despite the technological readiness of the Geological Survey of Norway, it required extensive coordination among government agencies over many years and recognition of the right political moment to convince authorities of the value of this work.

Onshore and offshore, GSOs are contributing to the integration of rapidly expanding amounts of data from new airborne and satellite instruments, which are in turn leading to new remote predictive mapping integrative methodologies that have the potential to greatly accelerate the geological mapping of the globe (**Lebel 2020**; **Smelror 2020**).

State of the world's Geological Survey organizations

Basic statistical information on most GSOs, such as number of personnel, operating budgets, etc., is not publicly available on the Internet. The authors of this volume have provided some basic information on their organizations (Table 1) to provide a snapshot of the current sizes of GSOs. Generally, the size scales to the gross domestic product of the country's economy, in terms of both number of employees and total budget (Fig. 1a–d), with the US Geological Survey and China Geological Survey correspondingly being almost an order of magnitude larger than other GSOs. The number of employees and total budget tend to be well correlated (Fig. 1e, f), suggesting that salaries are the largest component of most GSO budgets. In our sample, the Department of Mineral and Geoscience Malaysia and the Russian Geological Research Institute are outliers to the trend line, with a relatively large number of employees in relation to their budgets (Fig. 1b).

More detailed information is available on 37 GSO members of EuroGeoSurveys (EGS), an association of GSOs that has been active for more than 50 years (**Vidovic *et al.* 2020**). The mission of EGS is to provide Earth science knowledge to support the EU's competitiveness, social well-being, environmental management and international commitments (**Vidovic *et al.* 2020**). Since 1972, EGS has combined and coordinated the expertise of the member organizations to support the interests of the European Union and/or of the European Free Trade Association. A range of government ministries oversee the national GSOs of EGS. In 2016, EGS member organizations were overseen by ministries responsible for Environment (37% of the Surveys), Energy, Industry and Economy (26%), Research, Science and Technology (14%), and other (23%). According to the EGS statistics these proportions have been quite volatile with considerable back and forth between ministries of Environment and Ministries of Energy, Industry and Economy, reflecting perhaps the see-sawing of political parties and their priorities in democratic governments.

The overall workforce of EGS comprises several thousand professionals. The sum of permanent staff shows a significant reduction from more than 20 000 in 2006, to 11 000 employees in 2018

Table 1. *Statistical information on the Geological Survey Organizations represented in this volume*

Country	Organization	Gross domestic product (US$ million)*	Annual operating budget ($US million)	Number of employees
Canada	Geological Survey of Canada	1 730 914	66	401
China	China Geological Survey	14 140 163	1980	7500
Denmark	Geological Survey of Denmark and Greenland	347 176	40	285
Finland	Geological Survey of Finland	269 654	51	423
Germany	BGR	3 863 344	100	770
Illinois (US)	Illinois Geological Survey		21	170
Ireland	Geological Survey Ireland	384 940	17	100
Lithuania	Lithuanian Geological Survey	53 641	2	85
Malaysia	Department of Mineral and Geoscience Malaysia	365 303	16	1090
New Zealand	GNS Science	204 671	61	424
Norway	Geological Survey of Norway	417 627	29	196
Russia	Russian Geological Research Institute	1 637 892	57	1272
Sweden	Geological Survey of Sweden	528 929	47	281
UK	British Geological Survey	2 743 586	80	640
USA	US Geological Survey	21 439 453	1 160	7687

*Source: https://en.wikipedia.org/wiki/List_of_countries_by_GDP_(nominal)

(Fig. 2). A large part of this reduction was due to downsizing in Ukraine, from 9600 in 2006 to about 3000 in 2017. Whereas the statistics include the addition of countries (Russian Federation, Serbia and Spain–Catalonia) entering the EGS statistics for the first time, it is still notable that several European Surveys, including Albania, Denmark, France, Lithuania, Norway and the UK experienced severe staff reductions between 2006 and 2018. Data presented by **Lebel (2020**; his fig. 3) suggest a similar downsizing trend that started around 1985 in the Geological Survey of Canada, at a time when conservative policies focused on reducing the role of government and government taxation were spreading globally.

In contrast to the downsizing in Europe and Canada, GSOs in other parts of the world have been growing. Many countries have understood the fundamental role that GSOs can have in providing vital information for the social development in their countries: both economic, for optimal land-use, with respect to safety from geohazards and protection, and preservation of natural environments. The Geological Survey of China (CGS), established in 1999, has seen an annual increase year by year (**Yan *et al.* 2020**). Like most national Geological Surveys, CGS was established to plan and implement basic, strategic and public geological investigations. Today, CGS has more than 7500 employees in six regional centers, six professional Geological Survey Organizations and five innovation institutes (**Yan *et al.* 2020**).

Modern GSOs address a broad range of national issues that are required to build modern societies. Typically, these include resource, environmental, natural hazard and urban issues, but they vary considerably among GSOs. Figure 3 shows a summary of two key word analyses of the manuscripts submitted to this volume and represents a snapshot of the preoccupations of the authors, most of whom are senior figures within their GSO. Figure 3a represents a simple word count on selected topics, consolidated into six themes, whereas Figure 3a (based on the keywords in Table 2) represents a text analysis approach that not only uses word count but also examines sentences and word proximity to group the data into themes. While our small sample is biased towards economically developed countries, this meta-analysis shows that geological mapping and the search for natural resources (including minerals, petroleum and geothermal energy) represent the core business of most GSOs. While it may be surprising to a general reader that after decades of geological survey work GSOs continue with this traditional activity, mapping is only completed at a coarse granularity in most countries and the details needed for resource development are very often missing.

However, the most frequently cited keyword grouping after GSOs in the more detailed meta-analysis relates to sustainable development and most GSOs include groundwater, hazards and surficial geology in their mandates (Fig. 3b). Surprisingly, neither natural hazards nor climate change fall strongly out of the meta-analysis, which may reflect the splitting of mandates between different

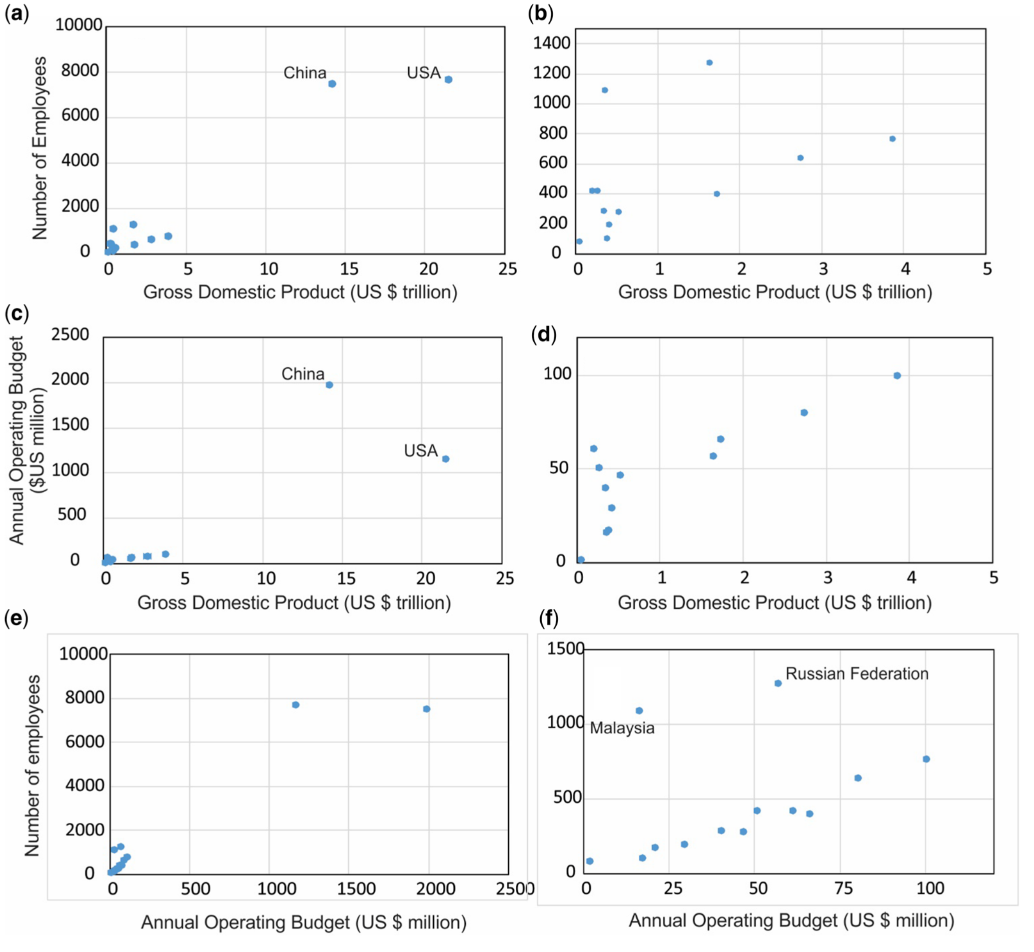

Fig. 1. Financial and staffing statistics for the GSOs that have contributed to this book from data in Table 1: (**a**) number of employees plotted against gross domestic product (GDP) for all GSOs; (**b**) same as (a) but excluding China and USA in order to see variation among smaller GSOs; (**c**) annual operating budget plotted against GDP for all GSOs; (**d**) same as (c) but excluding China and USA; (**e**) number of employees plotted against annual operating budget for all GSOs; (**f**) same as (e) but excluding China and USA. Financial and staffing numbers (Table 1) were obtained from the authors of this volume.

government departments and agencies, such as emergency management organizations, or perhaps the ambivalence of GSOs to shift their focus from the geoscience-driven extractive industry to the technology-driven renewable energy sector. Yet many increasingly recognize the opportunity to provide unique expertise to the deployment of low-carbon solutions, such as geothermal, nuclear and tidal energy. In particular, they are responding to the exponential demand for battery and other materials for e-vehicles (e.g. Li, Cd, Cu, Ni; Lu & Frith 2019) through focused research programmes.

Keyword mentions of big data and integration are very frequent, reflecting GSO preoccupations with the considerable accumulation of data over a century or more and the need to make this wealth accessible online for external users. In Europe for example, 31 of the 37 GSOs reporting in 2017 indicated work on data management (EuroGeoSurveys 2017). It is probably also a recognition of the potential for big data and artificial intelligence to solve complex problems.

A similar text analysis was conducted on the papers prepared for the last meeting of GSOs in 1992 (Bouchard *et al.* 1992; Table 3). Figure 4 represents a comparison of the top seven topics from that volume and from this volume. Most themes remain in similar positions. ‘Marine and seabed’ is

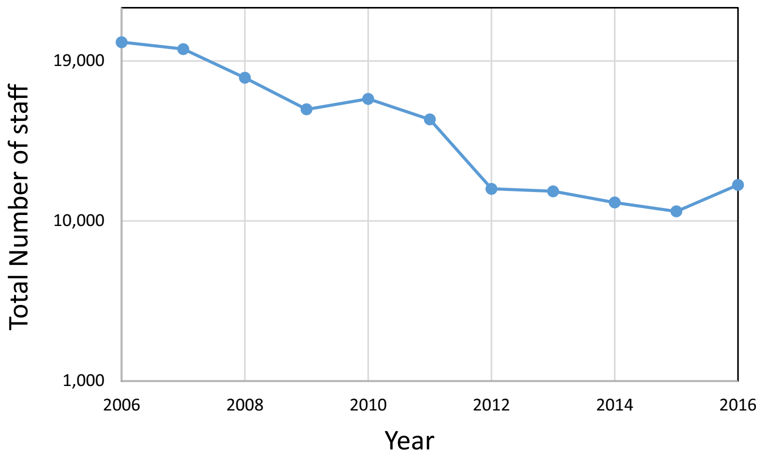

Fig. 2. Total number of staff in European GSOs from EuroGeoSurveys (2017) showing general decline in staffing levels.

a new theme that has emerged, reflecting the need for countries to define the outer limits of their continental shelf under the UN Convention on the Law of the Sea and to develop knowledge-based plans for sustainable development of their marine territories (UNCLOS; **Thorsnes *et al.* 2020**). The only theme to see a significant drop in ranking was international cooperation. It would be risky to read too much into this relative change, given the small sample size of the analysis, but this does raise flags in a world where economies are ever more globalized.

Changing roles of Geological Survey organizations

GSOs face a world of rapid change that will challenge them in both the short- and long-term future. The key challenges for GSO leaders are, first, to envision and influence the future and second, to transform organizations that are typically large bureaucracies with skewed demographic profiles, to address the looming issues. Several papers in this volume discuss how GSO mandates and activities have evolved over recent years.

The CGS is a relatively young organization and in this volume, **Yan *et al.* (2020)** presents an excellent example of a GSO with a modern mandate that derives directly from central government policy. As well as the mandate to explore for minerals and energy resources, CGS has the specific mandate to work on urban geology, poverty alleviation and Geo-environment (geohazards). The urban geology focus considers the use of underground space to depths of 2000 m for a variety of uses including transportation water storage and waste disposal, looking forward to putting in place urban development plans. The focus on poverty alleviation includes activity to provide drinking water and arrest desertification in karst regions within a future context of land use planning at a national scale. CGS efforts on geohazards include an extensive monitoring programme, detailed hazard mapping and zoning for over 2000 counties and cities. **Yan *et al.* (2020)** also puts emphasis on CGS's more fundamental geoscience, including a grand national programme on deep Earth exploration.

In some other countries, where the GSO has been in existence for longer, mandates have changed as a direct result of government legislation. **Azizi *et al.* (2019)** describe how the Geological Survey of Malaysia, which was set up in 1903 mainly to facilitate tin mining activities, was merged with the Department of Mines to form the Department of Mineral and Geoscience Malaysia. The objectives were to meet challenges linked to land use planning, groundwater resources management and mitigation of geohazards. The Malaysian Geological Act of 1974 is currently being revised, and the new Geological Survey and Geoscience Act includes key issues addressing climatic change, identification of environmentally sensitive areas, urban geology, forensic geoscience and marine geology. In addition, the Department of Mineral and Geoscience Malaysia has new strategic goals for sustaining ground water and new mineral and energy resources (rare earth elements, lithium, thorium, coal and coal bed methane and geothermal energy).

Similarly, as outlined by **Satkūnas (2019)**, laws that assert state ownership of the subsurface closely define the mandate and activities of the Geological Survey of Lithuania (GSL). In addition to a mandate

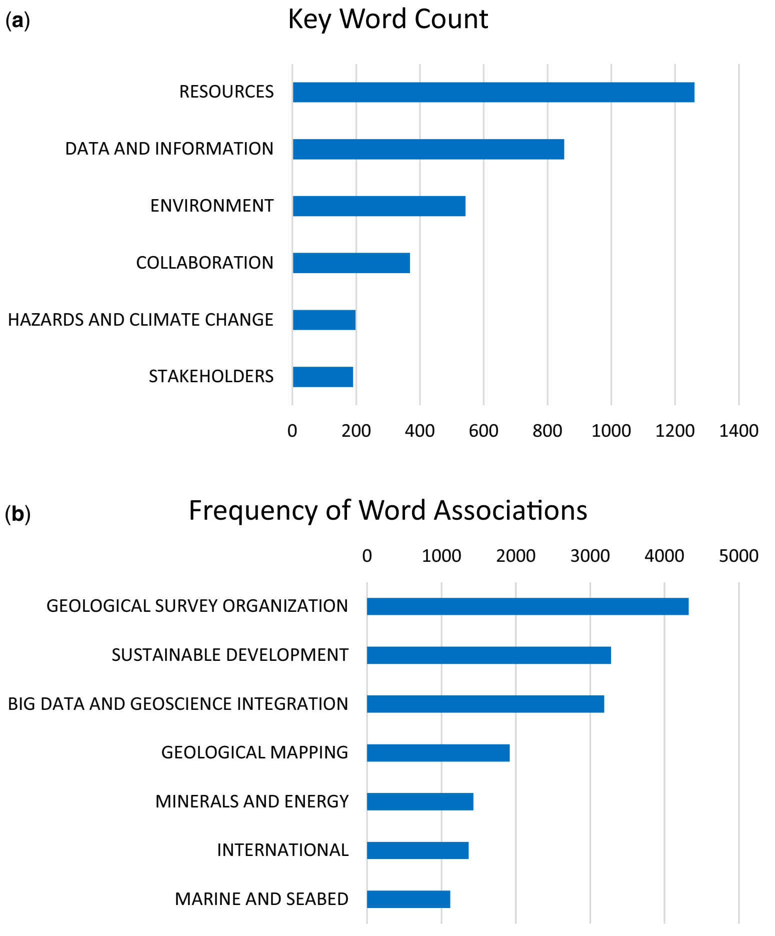

Fig. 3. Word count statistics from the papers included in this volume: (**a**) simple keyword count from the papers in this volume classified under major themes. Resources: includes ‘Resource’, ‘Mineral’, ‘Mining’, ‘Petroleum’, ‘Oil’, ‘Gas’, ‘Aggregate’, ‘Industry’, ‘Industrial’. Data and Information: includes ‘Data’, ‘Information’, ‘Publication’. Environment: includes ‘Environment’, ‘Environmental’, ‘Environmentally’, ‘Groundwater’, ‘Sustainable’, ‘Sustainability’. Collaboration: includes ‘Partner’, ‘Partnership’, ‘Cooperation’, ‘Collaboration’, ‘International’. Hazards and Climate Change: includes ‘Hazard’, ‘Climate’. Stakeholders: includes ‘Stakeholder’, ‘Communication’, ‘Public’. (**b**) using an interactive word association count (see Table 2).

for geological research and data services, the GSL also has an important regulatory function in the issuance of licences for mineral and hydrocarbon exploration, mining and groundwater exploitation. This has a number of advantages for GSL, including a clear direction to protect the subsurface environment and a legislated requirement for licensees to provide reports and data that can be included in the national database. However, the emphasis on licensing tends to result in heavy bureaucracy, which may demotivate scientists to pursue more research-oriented activities.

Countries endowed with rich mineral resources continue to put considerable emphasis on the natural resources function that came from their original mandate. For example, in Finland, Nurmi (2020) describes how GTK has evolved from vertically integrated mining agency to a world-leading mineral-oriented GSO. Although the basic mandate of GTK has remained the same, its strategic focus and mode of operation have changed considerably, typifying a pathway favoured by many GSOs. GTK has leveraged 130 years of history in mapping and studying mineral resources to develop a globally top-rank geodatabase. This expression of GTK’s profound knowledge of Finnish geology and mineral resources has had a crucial impact on the mining business in Finland. Today, GTK plays a vital role in providing

Table 2. *Results of text analysis on papers included in this book*

Geological Survey organization	Strategy; Management authority; SE SV dokument; Swedish national; PO box; Environmental protection agency; Groundwater resource; Local and regional; Denmark; Greenland; GEUS; Bulletin; Ice; Survey; Waste; Monitoring; Continental; Geological survey; Denmark And Greenland; Denmark and Greenland Bulletin; Continental Shelf; Ice Sheet; Continental Shelf Project; Camp Century; Greenland Ice Sheet; Inland Ice; Radioactive Waste; Kingdom Of Denmark; GNS; Zealand; Government; science; Research; Funding; GSI; Staff; Ireland; Business; Organisations; Review; Organisation; Sector; Partners; Opportunities; Focus; Institutes; Academia; Strategic; Companies; Geoscience; GNS science; Earth science; Research institute; Geoscience research; Science research; EGS; European; Eurogeosurveys; EU; Europe; Raw; Vision; EC; Materials; Commission; Strategy; Agenda; Common; Service; Members; United; Policy; Sharing; Efficient; Nations; Initiative; Action; Surveys; Framework; Sustainable; Geological Surveys; Raw Materials; European Commission; Sustainable development; United Nations; European Geological; European Union; National Geological Surveys; Geological Service For Europe; European Geological Surveys; Sustainable Development Goals; GSC; Canada; Generation; Canadian; Activities; Changing; Started; Mines; LED; Geoscience; Revolution; Present; Government; Field; Federal; Figure; Policy; Technologies; Economic; Political; Reports; Phase; Applications; Geological Survey of Canada; Federal government; Natural Resources Canada; SGSS; ISGS; Geologic; Geologists; American; Federal; State; Programs; Illinois; Public; Scientific; Address; States; Institute; Academia; Agencies; Support; Provided; National; USGS; Research; Act; Community; Institutions; Geosciences; Industry; Information; Organizations; Efforts; Government; University; Established; Program; Societal; Issues; State Geological; State Geological Survey; Illinois State Geological Survey; Geologic Mapping; Research Institute; Sweden; SGU; Swedish; Agency; Authorities; Agencies; Local; September; Accessed; Supply; Groundwater; Regional; Levels; Planning; Geological Survey of Sweden; Water Supply; Government Agencies; Groundwater Resources; Government Offices of Sweden; Local Authorities; Groundwater Levels; Lagar Dokument Svensk	4326
Sustainable development	Population; Growth; World; Increasing; Increased; Global; Demand; Change; Rapidly; Carbon; Climate; Impacts; Ecosystems; Trends; People; Future; Human; Energy; Efficient; Resource; Natural; Needed; Social; Increase; Sustainable; Resources; Planet; Solutions; Low; Rapid; Materials; Challenges; Economic; Oceans; Goals; Technological; Technologies; Major; Changing; Metals; Meet; Critical; Key; Economy; Nations; Production; Growing; Natural Resources; Climate Change; Sustainable Development; Soil; Development; Natural; Water; BGR; Resources; Life; Groundwater; Hazards; JMG; Environmental; Sustainable; Urban; Protection; Land; Economic; Energy; Comprehensive; Quality; Ground; Impact; Responsible; Fields; Geoscientific; Terms; Cities; Conditions; Department; Environment; Federal; Resource; Planning; Activities; Related; Climate; Management; Support; Cooperation; Ministry; Natural Resources; Sustainable Development; Climate Change; Earthquakes; Events; Plate; Monitoring; Activity; Seismic; Processes; Hazard; Types; Earthquake; Methods; Risk; Systems; Geohazards; Restoration; AL; Long; Ground; Deep; Understanding; Early; Remote; Deposits; Impacts; Major; Ecological; Include; Human; Global; System; Earth System; Geological Processes; Hazard and Risk	3281
Big data and geoscience integration	Learning; Machine; Artificial; Intelligence; Techniques; Big; Complex; Human; Questions; Advanced; Technologies; Data; Specific; Analysis; Geosciences; Sharing; Problems; Application; Models; Publications; Big data; Machine learning; Artificial intelligence; Earth system; Earth science; Open data; Earth system science; Big science; Data and information; Data discovery; Big; Integration; Driven; Earth; IUGS; Sciences; Science; Fundamental; Discovery; Approach; Solutions; System; Geoscientists; Goal; Initiative; Programs; Technology; Community; Issues; Scientific;	3188

(*Continued*)

Table 2. *Continued.*

	Revolution; Require; Scientists; USGS; Mission; Focus; Challenge; Digital; Questions; Efforts; Life; Comprehensive; Systems; Modern; Problems; Innovation; Program; International; Groups; Traditional; Long; Union; Collaboration; Earth science; Earth system; Data; Resolution; Information; Users; Models; High; AL; Tools; Maps; Open; Access; Urban; Developed; Effective; Surface; Large; Products; Provide; Areas; Database; Systems; Surveys; Map; Infrastructure; Detailed; Basic; Mapping; Planning; Seabed; Depth; Make; Key; Cities; Oceans; End; Communication; Geological Surveys; Geological information	
Geological mapping	Russian; Russia; Vsegei; Scale; Map; Maps; House; Geological; Continental; Tectonic; Shelf; Arctic; Committee; ST; Geophysical; Northern; State; Geological Survey; Geological Surveys; Geological mapping; Geological map; State geological; Geological maps; Continental shelf; Geological committee; Geological information; Geological research; Publishing house; Russian Federation; Handle; Net; Illinois; HTT; State; Survey; Geological; Geology; Geological Survey; State geological; Geological Surveys; State Geological Survey; Illinois State Geological Survey; Geological mapping; University of Illinois; Geological information; Geological research	1919
Minerals and energy	GTK; Finland; Mining; Exploration; Mineral; Minerals; Companies; Metals; Role; Deposits; Gold; Industry; Important; Materials; Innovation; Industrial; Expertise; Mines; Business; Resources; Sector; Raw; Mineral resources; Mineral exploration; Natural resources; Mineral deposits; Oil; Gas; Coal; Carbon; Energy; Basin; Fields; Production; Geothermal; Underground; Storage; Extraction; Source; Low; Million; Metals; Including; Oil and gas; Geothermal energy; Energy resources; Natural gas; Renewable energy; Oil and gas resources; Capture and storage; Clean energy; Energy resource; Fossil fuels; Low carbon; Oil fields; Shale gas; Energy storage; Energy supply; Million tons; Oil production	1429
International	Southeast; CCOP; Asia; East; Member; Countries; Organisation; Organisations; Region; Programmes; Geoscience; Capacity; Committee; Community; Cooperation; Quality; Sharing; Education; Communities; Building; Member Countries; East and Southeast Asia; CCOP member countries; Cooperating countries; Capacity building; Geoscience community; Developing countries; Cooperating countries and organisations; Geoscience big data; CCOP technical secretariat; IGCP; Leaders; Project; UNESCO; Projects; Developing; Scientists; Countries; Number; Funding; Years; Nations; IUGS; International; Project leaders; IGCP projects; IGCP project; Developing countries; Earth scientists	1367
Marine and seabed	Norwegian; Barents; Mareano; Sea; NOK; Proposal; Anon; Marine; Programme; Plan; Seabed; Ministries; Norway; Budget; Management; Ocean; Million; Ecosystem; Ngu; Institutions; North; Integrated; Funding; Shelf; Total; Ecosystems; Mapping; Coastal; Coral; Barents Sea; Norwegian Sea; Seabed Mapping; Mareano Programme; Management Plan; Million Nok; Coral Reefs; Marine Environment; Marine Research	1116

The analysis discriminated seven key topics (left column), based on the frequency of occurrence and association of key words (right column).

geoscientific expertise and specialist services for a wider range of stakeholders and commercial clients in government, the business sector, academia and the wider community, both in Finland and internationally. GTK is actively building new ways to cooperate with universities, research organizations and companies to support future development using cutting-edge technologies and to expand its own expertise. GTK plans to continue strengthening its role as a key player in the minerals sector innovation ecosystem, by focusing increasingly on the circular economy, digital solutions and water issues, which are essential factors for sustainable development through the 2020s and beyond.

Similarly, Lebel (2020) describes the changing national demand for geoscience that has led the Geological Survey of Canada (GSC) to evolve from a pioneering, exploratory, data-collecting organization in the 1840s to 1940s, to a more research-oriented organization. In common with Finland, but in contrast to Malaysia and Lithuania, this occurred in Canada without a substantial change in legislative mandate, but through incremental, and time-limited programme initiatives funded through central government. This

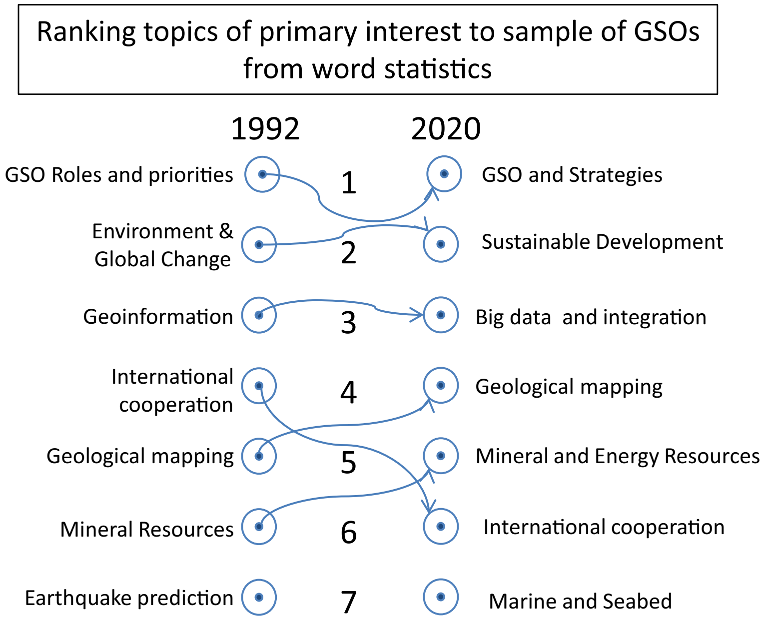

Fig. 4. Ranking of topics of primary interest to a sample of GSOs derived from word statistics. The 1992 rankings were obtained from meta-analysis of papers in Bouchard *et al.* (1992) and the 2020 rankings from the papers in this volume.

lack of renewed formal mandate presents challenges in terms of re-orienting the GSC's business model.

In concert with many other GSOs in Europe, the Geological Survey of Denmark and Greenland (GEUS) has moved towards a focus on environmental issues and long-term monitoring of environmental parameters such as groundwater quantity and quality and storage of radioactive waste (**Christiansen & Larsen 2020**). However, in the relatively unexplored regions of Greenland, more traditional geological survey work on basic geological mapping and resource assessment is continuing in addition to new tasks such as monitoring of the inland ice sheet and melt discharge.

To support sustainable development, the Geological Survey of Sweden over the past two decades has transitioned from a role as a 'knowledge bank' of traditional geological information to a more integrated source of online digital geoscience, environmental and geospatial data accessible to a wide variety of users across society (**Söderberg *et al.* 2020**). This has required a two-pronged approach – ensuring availability of societally relevant data and ensuring the information is easily understood and can be readily used.

Stumpf *et al.* (2020) describes a similar situation in the USA. The majority of states within the USA have a state geological survey. They are diverse and have evolved differently, reflecting each state's individual needs. Nearly all, however, focus on protecting land and water, mitigating geologic hazards and promoting sustainable development (**Stumpf *et al.* 2020**). All currently face challenges regarding effective data stewardship. The future roles of US state geological surveys will depend not only on providing scientific information, but also on legislative decisions at both state and federal levels and their ability to leverage support from existing and new collaborations with academia as well as federal, state, county and municipal agencies.

With state surveys taking on these direct public good and land use-related roles, the US Geological Survey has consciously adopted a broader, more integrative approach. As described by **Kimball *et al.* (2020)**, the US Geological Survey (USGS) has emphasized interdisciplinary science that addresses 'grand' issues of Earth system science through an innovative programme structure that includes mechanisms to enhance data integration, incorporation of technological innovation and cross-disciplinary synthesis of knowledge on complex public issues. The Community for Data Integration nurtures expertise in data generation, management and integration through proposal-driven projects on information technology. The Innovation Center connects scientists across the USGS with external partners with the aim of making next-generation technologies available to tackle complex societal

Table 3. *Results of text analysis on papers from Bouchard* et al. *(1992)*

No.	Topic	Keywords
1	Geological Surveys organization roles	State; BMR; Territory; Surveys; Geological; Commonwealth; Petroleum; Australia; Geoscience; Geoscientific; Mineral; Functions; Work; Government; Geology; Mapping; Continent; Resources; Responsible; Minerals; Responsibility; Industry; Detailed; General; Close; Mining; National; Agencies; Role; Survey; Csiro; Bureau; Australian; Land; Geological Surveys; Geological Survey; Mineral resources; National Geological Surveys; State Geological Surveys
2	Environment and global change	Water; USGS; Ground; Environmental; Change; Resources; Management; Focus; Studies; Protection; Global; Understanding; Quality; Hazards; Include; Environment; Earth; Emphasis; Systems; Continue; Century; Volcanic; Traditional; Mineral; Geologic; Growing; Land; Changing; Priority; Nation; Research; Energy; Data; Processes; Mineral Resources; Water Resources; Ground Water; Global Change
3	Geoscience information expertise	Expertise; Policy; Information; Resource; Governments; Geoscience; Required; Specific; Public; Knowledge; Effective; Natural; Meet; Opportunities; National; Advice; Development; Issues; Base; Economic; Human; Planning; Strategic; Good; Operation; Environment; Important; Cost; Maintain; Population; Systematic; Time; Geoscience information; National Geological Surveys; Geoscience information and expertise; General public; National geoscience; Sustainable development; Economic development; Public policy
4	International cooperation	International; Scientific; Unions; ICSU; IUGS; IGCP; Cooperation; Projects; Support; Exchange; UNESCO; Countries; Sciences; Activities; Congress; Governmental; Money; Members; Programs; Project; Union; Board; Program; Earth; Research; Organizations; Scientists; Earth Sciences; International Cooperation; International Geological; Scientific Research
5	Geological mapping	Approach; Maps; Mapping; Programme; Map; Core; Britain; Generation; Programmes; Strategic; Scale; Digital; Data; Increasingly; Radiometric; Geophysical; Activity; British; Systematic; Long; Field; Monitoring; Term; System; Time; Number; Regolith; Studies; Geochemistry; High; Cost; Major; Funding; Geochemical; Geological Mapping; Geological Maps; Data Sets; Geophysical Data; Mapping Accord
6	Mineral resources	Materials; Growth; Material; Rates; Consumption; Steel; Germany; Raw; Product; Figure; Metal; Total; Sectors; Increasing; Advanced; Source; Primary; Products; Iron; Industrial; High; Metals; Ceramics; Life; Growth Rates; Raw materials; Raw material; Average growth; Advanced materials; Gross national product; Growth rate; Industrial sectors
7	Earthquake prediction	Tokyo; Earthquake; Earthquakes; Prediction; Area; Greater; km; Hazards; Expected; Volcanic; Efforts; Central; Monitoring; Population; South; Active; Human; Japan; Earthquake prediction; Volcanic eruptions; Active Faults; Earthquakes and volcanic eruptions; Greater Tokyo Area; Term prediction

The analysis discriminated seven key topics (left column), based on the frequency of occurrence and association of key words (right column).

issues. The John Wesley Powell Center for Analysis and Synthesis provides support to groups of scholars to immerse themselves in the analysis and synthesis of information on complex questions.

Rattenbury *et al.* (2020) describes a different approach in New Zealand. GNS Science, New Zealand's GSO, has an applied Earth science research focus but without traditional government department accountabilities. As one of New Zealand's Crown Research Institutes established in 1992, the New Zealand Government owns GNS Science but the GSO has higher levels of self-determination, fiscal independence and impartiality than a government department. Research funding and commissioned research is a business imperative and because of this GNS Science is able to respond and adapt to changing societal expectations. GNS Science can also influence outcomes based on its discretionary research investment. New Zealand's geological setting astride an active plate boundary attracts many international partners endeavouring to understand geological processes in an accessible and logistically well-resourced natural laboratory. Partnerships like these substantially increase technological and financial resources, which in turn enable diverse and often ambitious projects.

Data management, big data

As mentioned in previous sections, the management, manipulation and synthesis of geoscientific and increasingly interdisciplinary data, has become a key task for GSOs all over the world. At its most basic, this translates to an increased emphasis on developing databases and web-based interfaces for serving the large amounts of data held by GSOs to stakeholders, including the general public. Transitions to 3D and 4D geological mapping and modelling have enabled GSOs to provide better quality information in more accessible formats to a larger and more diversified community of stakeholders. Increasingly, scientists and engineers are using 3D data in analysis of geological structures, supported by computerized 3D visualization, including the latest advances in virtual reality. These cost-effective tools enhance and improve visual exploration and communication, are easy to distribute and share, allow precise and accurate renderings, and help operationalize the use of the data in a variety of fields, including mining and groundwater management.

The increasing use of artificial intelligence tools in the exploration and manipulation of big data provides new opportunities for GSOs. In their paper, **Cheng *et al.* (2020)** outline these opportunities to and describes innovative technology for handling these data. Cheng has spearheaded the development of a Digital Deep Earth (DDE) initiative during his term as President of the International Union of Geological Sciences from 2016 to 2020. In his paper, he explores the questions of model validation and hypothesis testing, as well as the use of machine learning to achieve comprehensive knowledge discovery. Many challenges and opportunities remain, and it will be important to examine the role that government and professional organizations should play in facilitating the development and application of big data technology, including DDE.

International collaboration

As mentioned by several authors in this volume, collaboration across disciplines and borders is essential to address Earth systems science and global issues such as environmental degradation and climate change (**Kimball *et al.* 2020**). Looking forward, there is the likelihood of deep sea mining for rare minerals in international waters and the very real prospect of exploitation of the Moon and other planets (**Ludden 2020**), which will require significant international collaboration and agreement. Geology does not respect international borders and GSOs are well positioned to champion international collaboration and geo-diplomacy.

Petrov (2020) provides several good examples from the past two decades of multilateral projects that merge geological, geophysical and geochemical map data. One such example is the Atlas of Geological Maps of Northern, Central and Eastern Asia and Adjacent Areas at 1:2 500 000 scale, which was launched in 2002 by the Geological Surveys of China, Kazakhstan, Mongolia, Republic of Korea and Russia. Others are the Geological Map of Asia at 1:5 000 000 scale, launched in 2005, and the Atlas of Geological Maps of the Circumpolar Arctic at 1:5 000 000 scale, initiated in 2004 (Harrison *et al.* 2011; Petrov & Smelror 2015). These projects involve GSOs as well as national academies of sciences and universities from more than 30 countries. The International Union of Geological Sciences (IUGS), Commission for the Geological Map of the World at UNESCO, CIS Intergovernmental Council for Exploration, Use and Protection of Mineral Resources, as well as other international commissions, funds and institutions supported this effort.

At a global scale, GSOs have been involved and are currently engaged in a series of national and international geoscience programmes embracing a large variety of networks of research institutes, the industry, public organizations and other stakeholders. The International Geoscience Programme (IGCP; formerly the International Geological Correlation Program), which has been running for almost 50 years, is the oldest and most successful example of scientific cooperation between a non-governmental organization, the IUGS, and an intergovernmental organization, UNESCO (**Heirman & Lopes 2019**). Evaluation of IGCP, through statistical analysis of the annual progress report during four periods (1981–82, 1991–92, 2001–02 and 2011–12), provides insight into trends in the location of IGCP-supported projects, participating countries, involvement of developing countries and gender equality. Despite generally minimal financial support, IGCP has been successful in enabling and facilitating international collaboration between Earth scientists throughout the world. The programme has resulted in numerous new collaborations between the developed and developing worlds and between developing nations themselves. The IGCP brand still opens doors to new collaborators, new research and national funding agencies, often positively affecting the career of the involved researchers.

Many regions of the world have formal associations of GSOs. One of the longest standing organizations of this kind is the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP). **Lee *et al.* (2020)** describes the remarkable degree of cooperation between GSOs in the region.

Whereas CCOP comprises 15 national GSOs, its mission reaches well beyond national interests, with its stated primary mission being simply to deliver scientific information to the public. Its stakeholders include national and regional governments but also local authorities, regulatory authorities, planners and decision makers, investors, educational institutes and the general public. CCOP's promotion of partnership and collaboration, knowledge enhancement and sharing of both data and knowledge express its exemplary vision and values. CCOP is a model for international collaboration and has an ambitious plan to move forward in enhancing collaboration both between member countries and with other regional organizations, encouraging participation from new members, nurturing young geoscientists, connecting databases and analysing big data. Over its more than 50 years of existence, CCOP has evolved from an association aimed at development to a sustainable network of GSOs working together in mutual respect and for the benefit of the region.

As described earlier, Europe also has a strong formal association of GSOs. **Vidovic *et al.* (2020)** describes the work EGS is engaged in to create a pan-European service through sharing of data, infrastructure and capacities, joint research efforts and harmonizing geological data management. EGS supports the European Union in its transition to a low-carbon, climate-neutral, resource-efficient, socially and environmentally resilient economy, in compliance with the United Nations 2030 Agenda and the 17 SDGs. In 2017, EGS successfully launched the European Geological Data Infrastructure (EGDI). The EGDI web-portal gives access to a number of harmonized maps and geological, geophysical and geochemical datasets covering Europe. Furthermore, the EGDI provides open access to a very large number of national datasets from individual GSOs. By 2020, EGS will have established a common European Geological Knowledge Base and the 37 Geological Surveys comprising EGS will provide jointly a Geological Service for Europe.

There have been past attempts to build a global-scale international network of GSO, beginning with the first *International Conference of Geological Surveys* that was organized by the Geological Survey of Canada in Ottawa in 1992, on the occasion of its 150th anniversary. Despite multiple expressions of good will and intent, there have only been a few meetings at International Geological Congresses and other venues but no sustainable structure has been established. Nevertheless, the success of IGCP (**Heirman & Lopes 2019**) as well as recent collaborations on OneGeology, an initiative of the GSOs to make worldwide geoscience data web-available (Kemp *et al.* 2018), and DDE, the first IUGS-recognized big science programme (**Cheng *et al.* 2020**), suggest the potential feasibility of such an organization. In the Epilogue, **Lebel & Hill (2020)** report on past and present attempts to build an alliance of GSOs.

Conclusion

The papers in this volume provide a snapshot of how GSOs are faring in a rapidly changing world. Despite our best efforts to ‘corral all the horses’, the collection of papers is not as comprehensive as may be desired. Several prominent GSOs are missing from the collection and GSOs from regions such as Africa, South America and central Asia are entirely unrepresented. This simply speaks to the fact that organizing anything at a global scale is difficult for reasons of language, resources, culture and time zones, to name a few.

However, the snapshot represented by this volume illustrates that most, if not all, GSOs are working towards providing the scientific information and advice required to meet their national needs, which, in most cases, have been shifting over recent decades to managing the sustainable development of their countries. Such transitions are not simple and are often made more difficult by staff demographics that are out of phase with evolving needs. In this context, it is hard for GSOs to look outside the national interest and consider the planet as a whole. Yet GSOs are key global players, situated at the nexus of global sustainability. They have the scientific expertise to address complex global problems of geological, environmental and living systems and they are well situated to access and advise governments on sustainability policies. Therefore, it would be well worth the effort to build a strong network of GSOs to compare methods, share innovations and collaborate directly on the analysis and synthesis of information that would put world leaders and decision-makers on the same page with respect to global issues of sustainability.

The good news from this review is that the national trends and preoccupations of GSOs are pushing them to broaden the expertise of their research staff and to look outside for collaborations in order to solve their own complex issues. Now is perhaps the time to reinforce international collaborations through a global network of GSOs, or a network of networks such as CCOP and EuroGeoSurveys. To achieve this will require leadership and a focus on the big picture of global sustainability.

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