Australian Academy of Science

NATIONAL COMMITTEE FOR EARTH SCIENCES | AUSTRALIAN ACADEMY OF SCIENCE | OCTOBER 2018

Our Planet, Australia's Future

A decade of transition in Geoscience

A decadal plan for Australian Geoscience 2018–27

Australian Academy of Science

Our Planet, Australia's Future

A decade of transition in Geoscience

A decadal plan for Australian Geoscience 2018–27

NATIONAL COMMITTEE FOR EARTH SCIENCES | AUSTRALIAN ACADEMY OF SCIENCE | OCTOBER 2018

Acknowledgements

National Committee for Earth Sciences

Professor Sue O'Reilly AM FAA (Chair)

Professor Allan Chivas FAA (Deputy Chair)

Professor Kliti Grice FAA

Professor Richard Coleman

Professor Janet Hergt

Professor Anya Reading

Professor Chris Clark

Associate Professor Craig O'Neill

Dr Jessica Reeves

Dr Steve Beresford

Dr Andrew Barnicoat

Dr Phil McFadden AO FAA (Observer)

Professor Chris Rizos (Observer)

Professor Tim Rawling (Observer)

Dr Bill Shaw (Observer)

On behalf of the Australian Academy of Science, the National Committee for Earth Sciences gratefully acknowledges financial support from the Australian Research Council linkage program. The Learned Academies Special Projects (LASP) fund helped cover the costs of preparing this report. The National Committee also acknowledges the financial support of Geoscience Australia, the University of Melbourne, the University of Queensland, Macquarie University, and the Australian Geoscience Council. The Committee is also grateful to stakeholders who have contributed to the plan through various forms, including in-kind contributions, written submissions, consultation workshops, meetings and interviews. We also thank the many other members of the Australian geoscience community who assisted with the decadal planning process.

Special thanks to Professor David Cohen, from the Australian Geoscience Council, for providing expert advice on education and training matters.

Project management and editorial services were provided by the Australian Academy of Science Policy section—Dr Chris Hatherly, Dr Alistair Usher, Ms Samires Hook and Ms Meaghan Dzundza, and Dr Brent Davis who steered the decadal plan through its final stages.

These contributions are gratefully acknowledged.

ISBN 978 0 85847 594 6

Prepared by the Australian Academy of Science National Committee for Earth Sciences

Cover image: Prince Regent National Park, Western Australia. CREDIT: NASA / EARTHKAM.ORG / PUBLIC DOMAIN
Top back cover image: Taylor Glacier, Antarctica. CREDIT: FLICKR / ELI DUKE / CC BY-SA 2.0
Bottom back cover image: Lake Hume, New South Wales. CREDIT: FLICKR / TIM J KEEGAN / CC BY-SA 2.0

All URLs supplied in this plan were viewed April 2018 and were correct at the time of publication.

A digital version of this plan can be downloaded from
www.science.org.au/support/analysis/decadal-plans-science

Cite this plan as: National Committee for Earth Sciences (2018). *Our Planet, Australia's Future: A decadal plan for Australian geoscience 2018–27* (Australian Academy of Science)

Contents

A companion report to this decadal plan can be found on the Academy's website.

Elephant Rocks, William Bay National Park, Western Australia.

Sunset over the Marbles, Devils Marbles, Northern Territory.

A rift forms across the Larsen C ice shelf, Antarctica..
On 12 July 2017 this rift separated to form an iceberg that covers 5800km^2 and weighs over a trillion tonnes.

CREDIT: NASA / JOHN SONNTAG / PUBLIC DOMAIN

Preface

Geoscience is the study of Earth, its rocks, its origins and its processes—from the centre of the core to the crust upon which we live. This vital science comprehensively integrates the best and latest from physics, chemistry, biology, mathematics, and high-performance computation. It draws on the social sciences and economics to give life to that knowledge within the human community. It offers unique and profound benefits to Australian society, adding to the prosperity and quality of our lives.

As the human population continues to grow, with ever-increasing demands for food, energy, space, and mineral resources, the pressure on our planet rises. In this situation, geoscience is the interface between humans and the planet—it provides the knowledge that allows us to make informed decisions and act responsibly while continuing to enjoy the resources, services, and wonder that our planet provides.

In future, if we are to secure Australia's energy, food, and water supplies, as well as its mineral resources, it will be essential to have better geoscience knowledge and capability. At the same time, we will need to use geoscience knowledge to mitigate the impact of geohazards resulting from the dynamic nature of our planet and our interactions with it.

To move to a low-carbon, renewable-energy future, we will need to find and extract vast amounts of critical metals such as copper and cobalt. We will need lithium, rare-earth elements, and 'new' metals for computing, communications, and military technologies. However, we have already made the easy finds, and must now learn to explore in difficult new regions where mineral resources are deeply buried or hidden.

This plan identifies the coming decade as one of transition for geoscience—one which will see genuine predictive power concerning how our planet behaves, how it responds to the actions of its inhabitants, and where to explore for critical resources. This improved predictive power is the core of the vision and mission for Australian geoscience in the coming decade.

Vision

A collaborative, interdisciplinary geoscience community, developing a comprehensive understanding of our vast continent—and the planet—needing to responsibly manage Australia's resources, drive future prosperity, enable a sustainable, renewable-energy future, and enhance the quality of life for all Australians.

A companion report to this decadal plan can be found on the Academy's website.

Mission

To forge a deeper understanding of our complex planet and develop a new, predictive framework for the benefit of Australia, the geoscience community will:

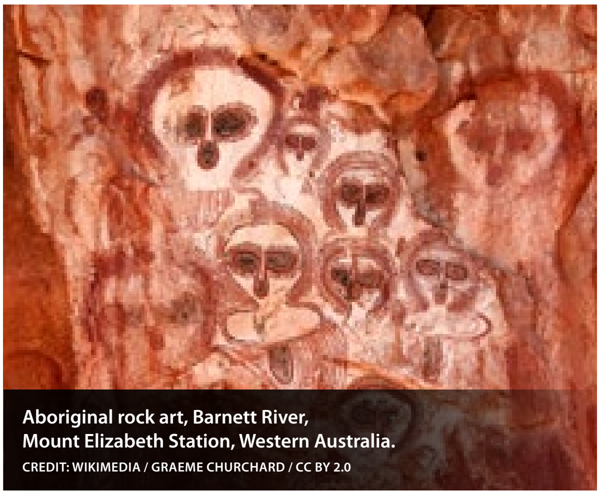
- continue to develop and provide scientific excellence in geoscience as a driver of the Australian economy and quality of life
- develop and deploy advanced knowledge and technology to better understand Earth processes and reveal our planet's past, present, and future, with the aim of maximising the continent's utility for Australians
- apply transformational imaging, as well as analytical, computational, and communication resources to better understand the where and why of Australia's natural resources. An expanded geoscience will rejuvenate mineral exploration and place Australia at the forefront of the science globally.

Executive Summary

The coming decade will be a critical period in human history. It will see humanity continue to place the planet under increasing pressure, ultimately calling for a new understanding of, and innovative approaches to, sustainability.

Geoscience will be a key component in providing the solution, in part by providing better access to vital resources, most of which are now either deeply buried or hidden. To discover and tap into these resources—which hold the key to our renewable future—the Australian geoscience community needs to develop and make available a vastly improved set of technological capabilities. It must embrace an integrated, whole-Earth perspective in both theory and practice, recognising that our planet is a truly complex system. Geoscientists must develop new technologies and pursue data-driven advances in key study areas and in modelling. They must increase knowledge, solve challenges, inform decision making, and offer ways to sustain resource discovery, extraction and remediation.

Geoscience deals with complex systems that occupy the interface between our planet and society, and that underpin many sectors crucial to our prosperity and future well-being. Agricultural productivity depends on knowledge of the underlying rocks, soils, sedimentary basins, and hydrological systems. Our mining, minerals, and energy sectors depend on geological expertise to develop exploration models which, in turn, are based on the latest geoscientific advances in understanding whole-Earth systems. Our ability to mitigate the risks associated with geohazards and climate change hinges on our knowledge of the processes that cause them.

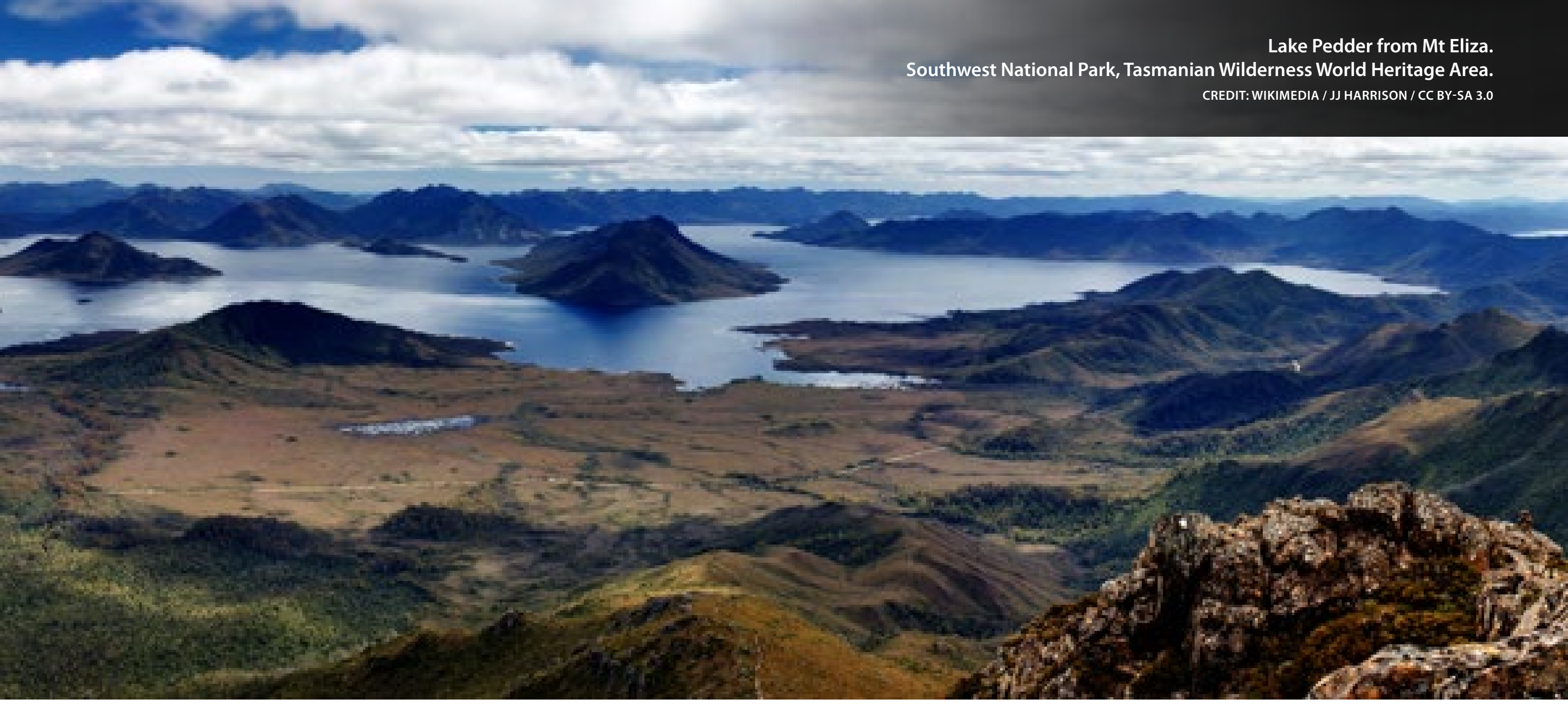


Aboriginal rock art, Barnett River, Mount Elizabeth Station, Western Australia.
CREDIT: WIKIMEDIA / GRAEME CHURCHARD / CC BY 2.0

The overarching grand challenge for geoscience in the coming decade is to develop accurate predictive power about how our planet will behave, how it will respond to our actions, and where to explore for critical resources. Solving this overarching challenge will give geoscience enormous capability with regard to the key societal challenges of food and water sustainability, our mineral resources future, our energy future, and our ability to deal with geohazards. It will add greatly to our ability to maintain the safety, security, wealth, and well-being of Australia.

To achieve this ambitious goal, it will be necessary to take a strategic approach to geoscience research. The strategy should lead to increased investment in infrastructure (particularly in better observational capability, as well as in data and computational capability), strengthening of national capacity in traditional geo-skills (while adding better capability in numeracy, data, computational capacity and better integration skills through an improved education agenda); and being smarter in accessing new capability in physics, chemistry, and mathematics. Finally, we will need to be more adept at collaboration within and between disciplines, including utilising new technologies and artificial intelligence in data acquisition.

Many poor—indeed disastrous—decisions have been made because of ignorance of the interconnectedness of Earth systems. Geoscience knowledge and its dissemination throughout the community and decision-makers is fundamental to preventing repetition of such mistakes.



Lake Pedder from Mt Eliza.
Southwest National Park, Tasmanian Wilderness World Heritage Area.
CREDIT: WIKIMEDIA / JJ HARRISON / CC BY-SA 3.0

Key strategic imperatives for the next decade

- Strong government support for critical infrastructure, in particular:
  - Creation of a 'downward-looking telescope'
  - Maintenance and improvement of super-computing capability
  - Acquisition and delivery of nationally coordinated broad-scale datasets through geological surveys and Geoscience Australia
  - National-scale repository for research data incorporating a national Laboratory Information Management System (LIMS) to ensure data provenance and integrity from sample to publication
  - Support for a National Drilling Initiative (NDI)
  - Maintain Australia's subscription to and involvement with the International Ocean Discovery Program (IODP)
- Ongoing government support for National Collaborative Research Infrastructure Strategy (NCRIS) facilities: particularly AuScope, Terrestrial Ecosystem Research Network (TERN), National Computational Infrastructure (NCI) and the Pawsey Supercomputing Centre, Bioplatforms Australia (BPA), the Australian Microscopy and Microanalysis Research Facility (Characterisation), the Australian National Fabrication Facility (Fabrication), and the Synchrotron
- A high-impact research agenda that will drive major advances in the predictive capability of Australian geoscience
- Strong government and community support for the UNCOVER initiative
- Increase the number of CRCs and ARC centres of excellence targeting research relevant to Australia's strengths and future needs, and ensure they are strategically aligned to increase the predictive capability of geoscience
- Broad-scale exposure of Australians to the geosciences, particularly throughout early childhood to pre-university school curricula
- Maintain and improve capability in the traditional geology, geochemistry, and geophysics skills while increasing the number of highly numerate students engaging in tertiary and post-graduate geoscience courses
- Increased simulation and modelling capacity focused on predictive capability
- Ensure that physicists, chemists, mathematicians, and computational and data scientists are aware that geoscience provides satisfying, interdisciplinary and translatable career opportunities
- Ensure that other science disciplines are aware of the strengths that formal training in geoscience provides for dealing with large, complex data sets, unconstrained systems, and very large scales in both space and time
- Strategic leadership that coordinates both research and industry efforts
- Strong government support for physics, chemistry, mathematics, and computational and data science.

The 2002 Blue Marble featured land surfaces, clouds, topography, and city lights at a maximum resolution of 1 kilometre per pixel.

1 Introduction

"OUR CONNECTION WITH EARTH IS THEREFORE NECESSARILY INTIMATE AND INHERENTLY COMPLEX."

Earth is an intricately complex system that underpins the very existence of life. The crust—the outer hard layer of Earth—is made up of different types of rocks formed at different times in Earth's evolution. Everything we see on our planet, everything we build, use, and value, all the plants and animals that enrich and facilitate our lives, everything we grow and eat—and indeed we ourselves—are ultimately derived from the substances of these rocks and their interactions with the broader processes of our planet.

Our connection with Earth is therefore necessarily intimate and inherently complex; the services provided by our planet sustain our very existence and everything we do.

As the human population continues to grow, with ever-increasing demands for water, food, mineral resources, space, and energy, there is intensified pressure for our planet to provide. Astoundingly, human activity now challenges, and in many instances exceeds, nature as an agent of geological change. In Australia, human activity now moves many more times the amount of geological material than is moved by natural erosion. The International Energy Agency estimates that our rapidly increasing human 'energy system' now operates at about one-third the rate of the energy transferred in moving all the continents, making all the mountains, the earthquakes, and the volcanoes on our planet.[1]

Given the amazing demands we now make and will continue to make of our planet, and the increasing number of people at risk from the hazards of this dynamic planet, the coming decade for geoscience will be one of transition. This will necessarily involve a transition to providing the utmost predictive power in understanding how our planet behaves, how it responds to the actions of its human inhabitants, and where to explore for critical resources. Geoscience must fully describe the critical interface between humans and the planet; it must provide the knowledge base for us to act responsibly and to live within the carrying capacity of the planet while continuing to enjoy the resources and services it provides.

Hence Australian geoscience over the coming decade will be motivated by two powerful drivers. One is a thirst for new knowledge to satisfy the intrinsic human need to understand the world we live in. The other is an overarching grand challenge: to become truly predictive so that we can confidently and successfully apply our geoscience expertise to societal challenges. To meet such a challenge we will need to improve management of land, water, energy, and mineral resources; minimise loss of life and property from natural disasters; facilitate wealth generation; and enhance and protect our quality of life.

Given that solving these issues is a significant public-good, this document is intended to inform the Australian Government, government agencies supporting education and research relevant to the geosciences, and the other stakeholders—geoscientists, universities, education institutions, professional associations, industry, and associated peak bodies.

1 See, for example: https://theconversation.com/our-effect-on-the-earth-is-real-how-were-geo-engineering-the-planet-1544

Kati Thanda–Lake Eyre, South Australia, viewed from the International Space Station.
CREDIT: NASA / USGS / LANDSAT / CC BY 2.0

2 Australia's global geological setting

"GEOSCIENCE SITS ON THE CUSP OF BEING ABLE TO SOLVE PREDICTIVE PROBLEMS THAT WERE PREVIOUSLY INTRACTABLE."

The geology of each continent and its position on Earth defines its surface expression, climate, ecosystems, and human habitability. The geological foundation of a country has a profound impact on where its peoples live, the hazards they face, the industries they create, their wealth, and their lifestyles. It defines who they are. Connection to country is defined primarily and nurtured through understanding Earth's processes and how best to work in balance with them.

Australia occupies an entire continent: an old continent under tectonic compression, the flattest continent, and the driest inhabited continent, with the broadest and most populated interface with the Southern Ocean. Australia's marine jurisdiction covers an area almost twice the size of its land mass and 4 per cent of the global ocean. We have warm currents down both the east and west coasts. We have abundant energy and mineral resources, but almost two-thirds of the continent is hidden under cover that obscures potentially mineralised rocks[2].

Australians live predominantly along a narrow coastal strip and, as much as any peoples on the planet, our economy and lifestyle have been built on the primary capability of our land—agriculture, resources, and energy. To a large extent this has been dictated by the geographical and geological setting of our vast and tectonically stable landmass, and it is inevitable that we will need to continue to rely on this primary bounty long into the future.

As noted above, human activities are now having a significant impact on Earth's dynamic processes and even its geology; we have entered a new epoch known as the Anthropocene. Earth and its ability to provide the resources essential for habitability are changing rapidly; our activities are testing Earth's capacity to provide for us and we are changing its dynamics.

In many respects this is particularly important for Australia, and this challenges long-held assumptions. As the population of Australia grows (exceeding 30 million by 2030) and the demands on our continent's resources intensify, living sustainably takes on new urgency. Our national wealth and quality of life will depend on how effectively we can manage competing interests in resources on our finite continent.

Our geological and geographical settings mean that many of the issues we face are uniquely Australian and must be solved by us; we cannot rely on others to solve them for us. Furthermore, it must be recognised that Earth is a large complex system, and so we will not gain an effective understanding of our planet by studying different components of it in isolation. We need to study our planet in a holistic sense using a broad-based, multi- and inter-disciplinary approach. This has significant consequences for the way we must do our science; we must understand our planet as an integrated system—from the deep Earth, up through the mantle, the lithosphere, and the crust—and we must understand the interactions with the atmosphere, hydrosphere, cryosphere, and biosphere. This requires the removal of boundaries between different research communities so geoscience can make a strong contribution to the broad compass of a holistic Earth Science capability, embracing the whole Earth system of the oceans, the atmosphere, exosphere, ionosphere, and biosphere—as well as the geosphere.

This presents geoscience with enormous challenges in terms of both opportunities and responsibilities. However, recent and ongoing technological developments—in data and computational capability, new data acquisition sensors in geochemistry and geophysics, remote sensing from space, and positioning capability—mean that, by addressing research questions of much larger and complex-system scope, geoscience sits on the cusp of being able to solve predictive problems that were previously intractable.

2 Blewett, RS (ed.) 2012, *Shaping a nation: a geology of Australia*, Geoscience Australia and ANU Press, Canberra

Undergraduate geology students at Weekeroo Station, South Australia.
CREDIT: NATHAN DACZKO

3 Australia's geoscience community

"AUSTRALIAN GEOSCIENCE HAS ENJOYED REMARKABLE SUCCESS IN ITS TWIN CHALLENGES OF DEVELOPING A COMPREHENSIVE UNDERSTANDING OF OUR VAST CONTINENT AND DRIVING PROSPERITY."

In Australia, geoscience research is primarily carried out within higher educational institutions, by government agencies such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Geoscience Australia, by industry, and industry-led Cooperative Research Centres (CRCs). It is also being undertaken by departments and agencies not traditionally associated with the geosciences.

Australian geoscience has enjoyed remarkable success in its twin challenges of developing a comprehensive understanding of our vast continent and driving prosperity. Geology leads the science, technology, engineering and mathematics (STEM) sub-fields for which Australian citation rates are higher than those for the United States and the EU15[3]. The direct economic contribution of the minerals industry, underpinned by geoscience, was 8 per cent of Australian GDP in 2015 and almost 60 per cent of exports.

Geoscience Australia and the state and territory geological surveys provide strength and stability to Australian geoscience.
CREDIT: GEOSCIENCE AUSTRALIA

3.1 Higher education institutions

University-based scientists are responsible for much of the curiosity-driven geoscience research carried out in Australia. This research, which tends to reflect the interests and skills of individual geoscientists, is primarily supported by ARC Discovery Grants.

Research of a more strategic or applied nature is also undertaken by academics, with funding support from a range of sources such as ARC Linkage Grants, the CRC Program, AMIRA International, and direct industry grants.

Both curiosity-driven and strategic research are supported by the ARC centres of excellence.

Individual departments from different universities have grouped together to produce outstanding centres such as GEMOC[4], CODES[5], and the CET[6].

3.2 Research in government agencies and geological surveys

The overwhelming majority of geoscientists employed by government agencies work for Geoscience Australia, CSIRO, or a state or territory geological survey. Geoscientists employed by government agencies undertake research of a strategic or agency-mandated nature. Research goals tend to be determined corporately, with individual geoscientists applying their geoscientific skills to the realisation of these goals.

3 Office of the Chief Scientist, 2014. *Benchmarking Australian Science, Technology, Engineering and Mathematics.* http://www.chiefscientist.gov.au/2014/12/benchmarking-australian-science-technology-engineering-mathematics

4 The GEMOC ARC National Key Centre: http://gemoc.mq.edu.au

5 The Centre for Ore Deposit and Earth Sciences: http://utas.edu.au/codes

6 The Centre for Exploration Targeting: http://cet.edu.au

3.3 Geoscience Australia and state and territory geological surveys

As well as undertaking carefully targeted strategic research, Geoscience Australia and the state and territory geological surveys provide enormous strength and stability to Australian geoscience by undertaking national- and state-scale geological, geophysical, and geochemical surveys and releasing the results as public-good data. These activities provide a critical data infrastructure for the national geoscience research and industry effort.

Opalised bivalve from the Coober Pedy Opal Field, South Australia.
CREDIT: FLICKR / JAMES ST. JOHN / CC BY 2.0

3.4 Industry

Approximately half the geoscientists employed by industry are in the mineral, petroleum, and gas sector, with the majority of the others in business services and consulting engineering.

Research undertaken by geoscientists employed by industry tends to be of an applied nature, focusing on current and perceived future sectoral needs. Industry also contributes financial and other forms of support to a range of research undertaken by academia and government agencies.

Some peak bodies coordinate industry research on a collaborative basis, developing and managing jointly funded research projects on a fee-for-service basis on behalf of members. For example, by taking a partnership approach to research and development, AMIRA International members are able to enhance their competitive position through access to leading-edge research and technology. Other bodies, such as the Minerals Council of Australia (MCA), advocate concerns and promote issues of relevance to the minerals industry and assist with funding specific educational initiatives such as the National Exploration Undercover School (NExuS) at the University of Adelaide[7].

3.5 Cooperative research centres

The CRC Program supports industry-led collaborations between industry, researchers, and the community. It aims to improve the competitiveness, productivity, and sustainability of Australian industries and to foster high-quality research to solve industry-identified problems. The program supports research and development and education activities that achieve outcomes of national economic and social significance.

Australian geoscience has, in the past, been well served by the CRC Program. In 2002–03, there were eight mining and energy CRCs. Five new CRCs that commenced in the 2003–04 round were of particular relevance to the geosciences.

Currently there is only one mineral exploration-related CRC[8] (the DET CRC[9]) and its funding is coming to an end. There is potential for new geoscience CRCs for discovery and definition of mineral deposits.

It is strategically imperative for the geoscience community to have many more successful CRC bids if we are to solve the problems that will impact on the wealth of Australia.

7 The National Exploration Undercover School: https://nexus.org.au

8 CRC CARE (Contamination Assessment and Remediation of the Environment) overlaps with the wider Earth and environmental sciences. See CRC CARE: https://www.crccare.com

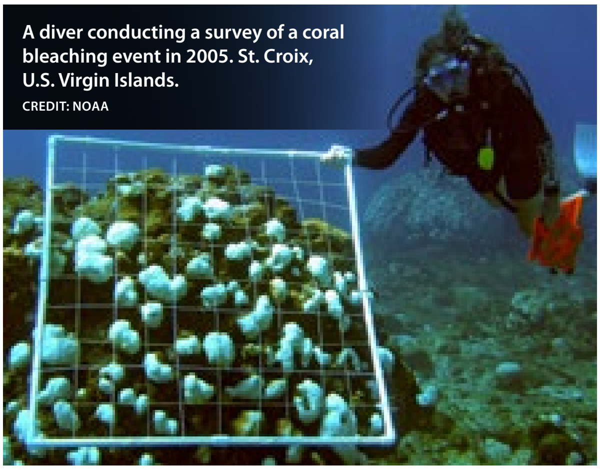
9 The Deep Exploration Technologies CRC: http://detcrc.com.au

Geoscience Australia headquarters in Symonston, Canberra.
CREDIT: WIKIMEDIA / BIDGEE / CC BY-SA 3.0

3.6 ARC centres of excellence

ARC centres of excellence are designed to be prestigious foci of expertise through which high-quality researchers maintain and develop Australia's international standing in research areas of national priority.

In the 2011 round for the Centres of Excellence, funding was provided for the Centre of Excellence for Geotechnical Science and Engineering[10] and for the Centre of Excellence for Core to Crust Fluid Systems[11]. No geoscience sectors were funded in either of the 2014 or 2017 rounds. As with the CRC Program, it is a strategic imperative for the geoscience community to have more successful bids for relevant ARC centres of excellence.



A diver conducting a survey of a coral bleaching event in 2005. St. Croix, U.S. Virgin Islands.
CREDIT: NOAA

3.7 Professional societies

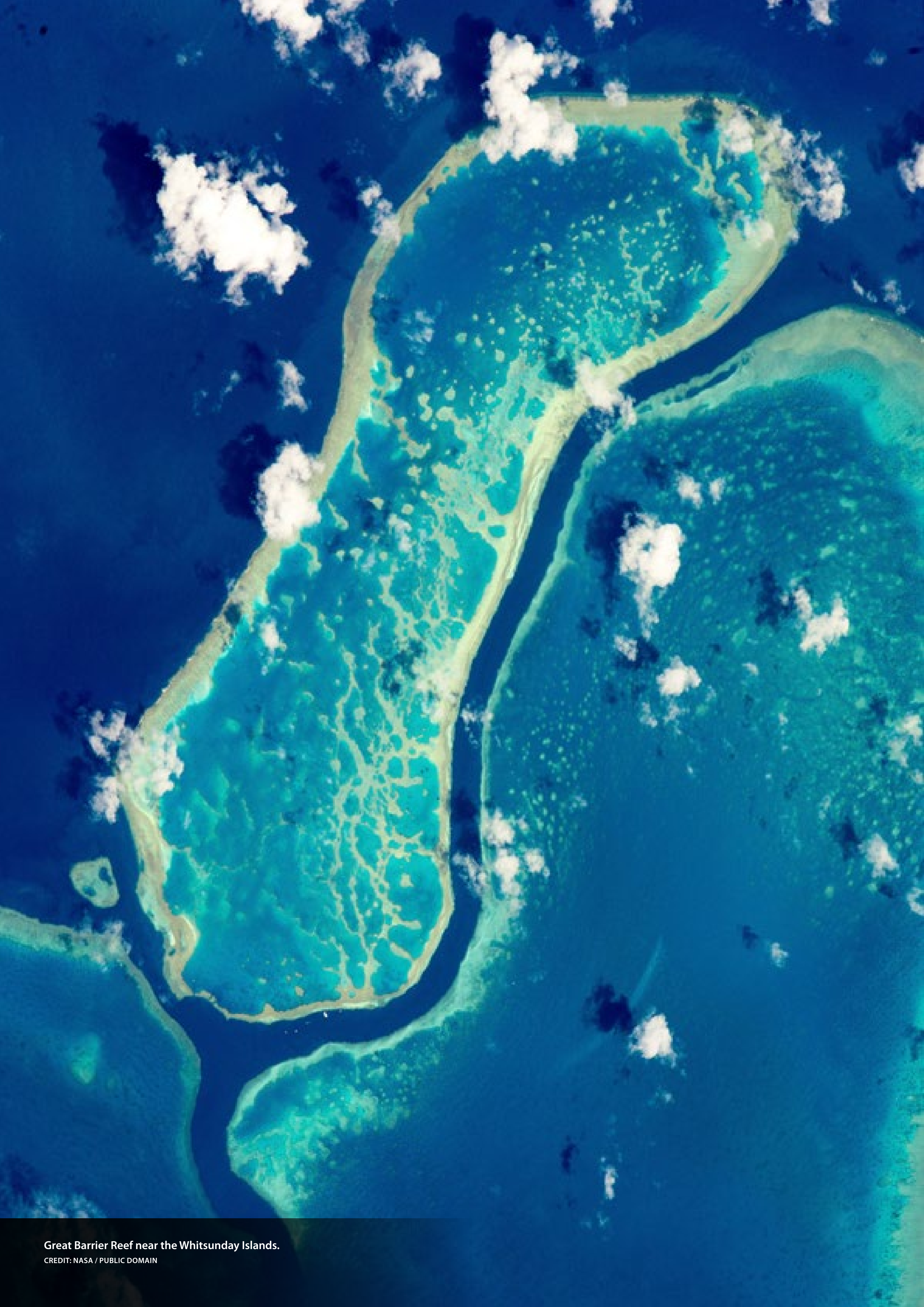
Professional organisations play an important role in maintaining the effectiveness and coherence of the geoscience community through professional accreditation, support of scientific publication, sponsorship of conventions and conferences, representing the community to government, and providing educational programs.

The Australian Geoscience Council (AGC) is the peak council of geoscience organisations in Australia. It represents eight major Australian geoscientific bodies: the Association of Applied Geochemists (AAG); the Australian Geoscience Information Association (AGIA); the Australian Institute of Geoscientists (AIG); the Australian Society of Exploration Geophysicists (ASEG); the Australasian Institute of Mining and Metallurgy (AusIMM); the Geological Society of Australia (GSA); the International Association of Hydrogeologists Australia (IAHA); and the Petroleum Exploration Society of Australia (PESA).

Through its member organisations, the AGC represents over 8 000 geoscientists comprising industry, government, and academic professionals in the fields of geology, geophysics, geochemistry, mineral and petroleum exploration, environmental geoscience, hydrogeology, and geological hazards. These organisations are vital to the well-being of the geoscientific community.

10 The Centre of Excellence for Geotechnical Science and Engineering: http://cgse.edu.au

11 The Centre of Excellence for Core to Crust Fluid Systems: http://ccfs.mq.edu.au



Great Barrier Reef near the Whitsunday Islands.
CREDIT: NASA / PUBLIC DOMAIN

4 The key challenges

"GEOSCIENCE MUST GROW AND CHANGE IN THE COMING YEARS. TO RESPOND TO THESE KEY CHALLENGES, IT MUST REACH A HOLISTIC PERSPECTIVE WHICH IS BOTH WIDER AND SYSTEMS-BASED."

As our demands upon Earth grow, providing the knowledge base for us to act in a responsible manner—while continuing to enjoy the resources and services that our planet provides—will present many challenges to geoscience. At the strategic level those challenges can be grouped into four areas: food and water, mineral resources, energy, and geohazards. These are also recognised in the 2016 National Science and Research Priorities.

The Australian Government's Industry Growth Centres (IGC) Initiative is designed as an industry-led approach driving innovation, productivity, and competitiveness by focusing on areas of competitive strength and strategic priority. The Australian Government has signalled that three of the geoscience key challenge areas are strategic national priorities by creating three of the six IGCs in these sectors:

- the Oil, Gas and Energy Resources Centre, known as National Energy Resources Australia (NERA)
- the Mining Equipment, Technology and Services Centre, known as METS Ignited
- the Food and Agribusiness Growth Centre, known as Food Innovation Australia Ltd (FIAL).

4.1 Food and water sustainability

Increasing urban size and density has brought Australia's food and water resources into sharp focus. Particularly in rural areas, our water resources are scarce, highly variable, and subject to strong competing interests. Maximal agricultural productivity relies on a detailed knowledge of the rocks, minerals, and soils that underlie our food-generating land areas, and which provide the basic nutrients and act as a container for water. Earth resources are used for fertilisers and other products used in agriculture. Groundwater access and management is a major and growing issue in Australia.

Food production is increasingly supported by automated systems controlled by Global Navigation Satellite Systems (GNSS), which are underpinned by geodesy. Technology such as this was identified as one of the major research directions for agricultural science[12] and has been dramatically improved in Australia by AuScope.

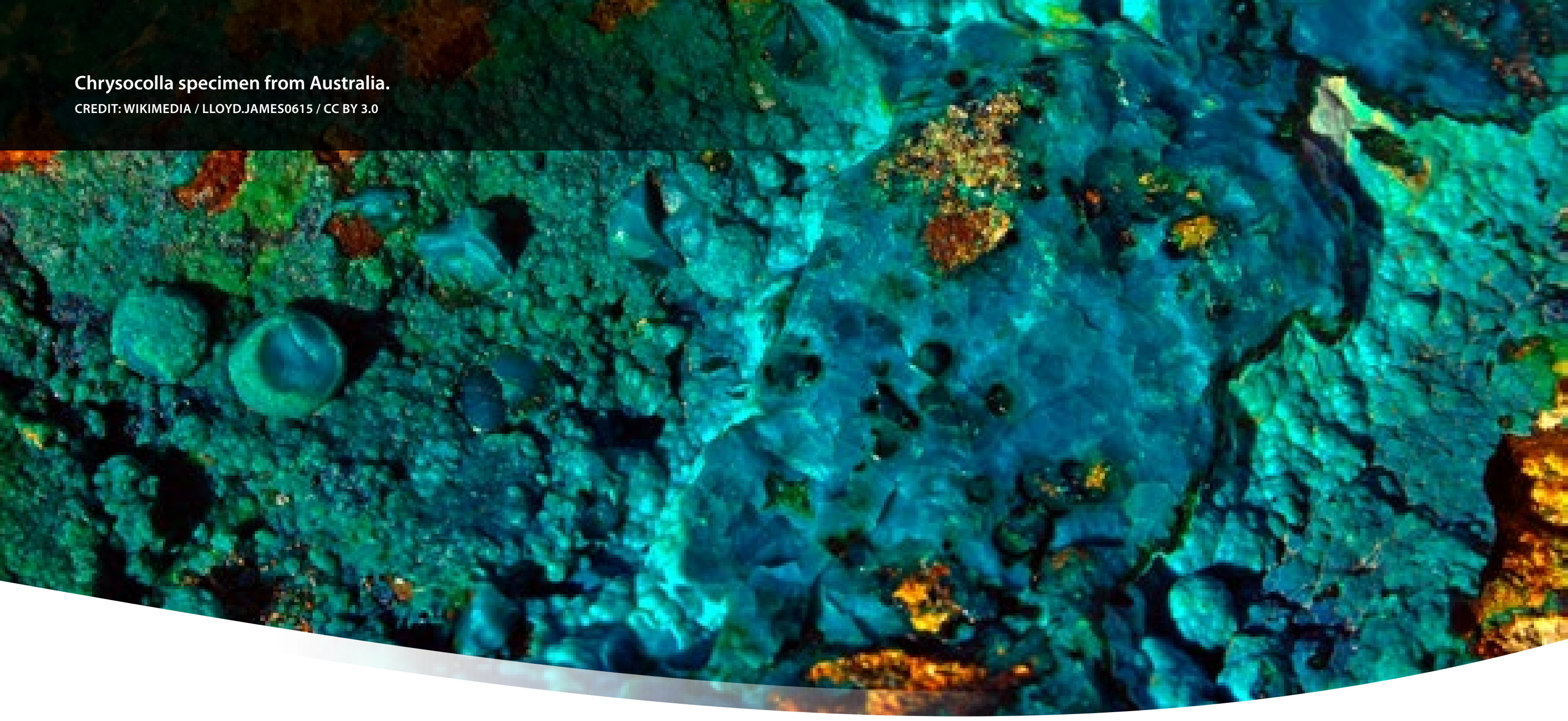
The basic knowledge required for groundwater management includes its geological container, the interconnectedness of different containers, and understanding the pore-space resource. Providing this knowledge is a geoscience responsibility.

Several national drilling initiatives are planned in regions of shallow cover over the next decade to provide monitoring and observational infrastructure relevant to groundwater and soil science. Collaborative co-location of infrastructure by AuScope, TERN, and other national research infrastructure providers will allow unprecedented integrated monitoring of Earth, enabling us to understand and manage these precious resources using a whole-of-geological-basin approach.

Geoscience will contribute to maintaining and increasing Australia's agricultural productivity by continuing to develop programs in collaboration with farmers and agricultural organisations, all of which will aim to maximise our productivity using the latest, cutting-edge technologies[13].

12 Australian Academy of Science 2017: *Grow. Make. Prosper. The decadal plan for Australian Agricultural Sciences 2017–26*

13 See, for example: National Committee for Agricultural Science, 2017. *Grow. Make. Prosper. The decadal plan for Australian Agricultural Sciences 2017–26.* https://science.org.au/support/analysis/decadal-plans-science/decadal-plan-agricultural-sciences-2017-2026



Chrysocolla specimen from Australia.
CREDIT: WIKIMEDIA / LLOYD.JAMES0615 / CC BY 3.0

4.2 Australia's mineral resources future

Mineral resources provide the basis for critical aspects of our society: iron for industry, copper for electrical systems, cobalt for electric cars, and lithium, gold, and rare-earth elements for computing communications, batteries, solar cells, and military technologies. As we move into the future, many of these resources will be in critically short supply, both in Australia and overseas; this scarcity will be a threat to Australia's well-being.

Australia's—indeed the world's—shift towards renewable energy sources and electric cars will involve massively greater demand for copper, cobalt, gold, tantalum, rare-earth elements, and other specialty metals. Predicting which elements will be required may not be possible beyond the near- to medium-term, meaning that, more than ever, we require an agile exploration sector linked to a strong research community.

The Australian minerals industry has a long history of innovation that has underpinned its success and Australia's economy—and continues to do so today. The industry's direct economic contribution in 2015 was 8 per cent of GDP and almost 60 per cent of exports. This figure neglects the total value of the sector to Australia's innovation system. The minerals industry and those that support and benefit from it—mining equipment, technology, and services (METS)—have been described as a 'dynamic minerals innovation complex' that extends far beyond commodity extraction (using 'mining' in the broadest sense).

Australia's rich mineral and energy endowment and our historical success at finding resources near the surface is well established. But our ability to find and access mineral resources in the approximately three-quarters of our continent under post-mineralisation cover is poor. With the exception of iron ore, coal, and petroleum, Australia's current extractable resource base will decline dramatically in the next decade, with serious consequences for our national wealth and manufacturing capabilities. More fundamental research is required to support exploration in the covered areas of Australia for copper, cobalt, base metals, rare-earth elements, gold, lithium, and other non-bulk minerals crucial for our future.

To achieve increasing success in the discovery of these hidden resources, the geoscience community must undertake research on mineral systems and the processes that foster them, in collaboration with the exploration and mining communities. Mineral systems form through a complex interplay between the crust, atmosphere, hydrosphere, cryosphere, and biosphere, and ultimately derive from the movements of the crust and the upwelling of heat and components from the deep Earth (i.e., the core and mantle). All of these components have changed over the 4.56 billion years of Earth history: as the planet cooled, the core and mantle formed, the atmosphere/hydrosphere changed, life evolved, and the tectonic plates started to interact across Earth's surface. Geoscience in Australia must therefore acquire a greater understanding of these interactions and develop a comprehensive 4-dimensional (3D through time) model of Earth. The aim is to maintain access to critical resources through mineral exploration and mining, keeping it as a driving force of the Australian economy for decades to come.

The opportunity cost of not preparing for future minerals development is high. Australia must develop the capability to find new deposits under cover, and so maintain our place in the growing global market for high-value minerals. This is an important challenge that the UNCOVER Australia initiative[14] seeks to address. The goal is to create the scientific knowledge and new technologies necessary to lift the success rate of mineral exploration in the covered areas of Australia to the same levels enjoyed 30 years ago in uncovered areas.

14 UNCOVER Australia: http://uncoveraustralia.org.au

Azurite, Burra Mine, South Australia.
CREDIT: WIKIMEDIA / JJ HARRISON / CC BY-SA 3.0

Dundasite (white) and Crocoite (orange), Dundas, Tasmania.
CREDIT: WIKIMEDIA / JJ HARRISON / CC BY-SA 3.0

The Australian Government's creation of METS Ignited, with the aim of improving collaboration and strengthening relationships between Australian METS firms, mining companies, researchers, investors, and government, is welcomed as an important initiative. However, having an internationally recognised and thriving METS sector relies on a thriving mining sector which, in turn, relies on a pipeline of rich mineral finds based on successful mineral exploration. As already indicated, Australia now faces significant challenges with regard to successful mineral exploration. Because of the cover across most of Australia, success rates in mineral exploration have dropped dramatically over the past two decades; in that same period global investment in Australia has gone from approximately one-quarter of the world's mineral exploration expenditure to approximately one-eighth. Thus we face a self-reinforcing downward spiral in support for the METS industry—unless the UNCOVER Australia initiative is supported and we can solve the problem of exploring successfully in the covered areas of the continent.

Copper and cobalt

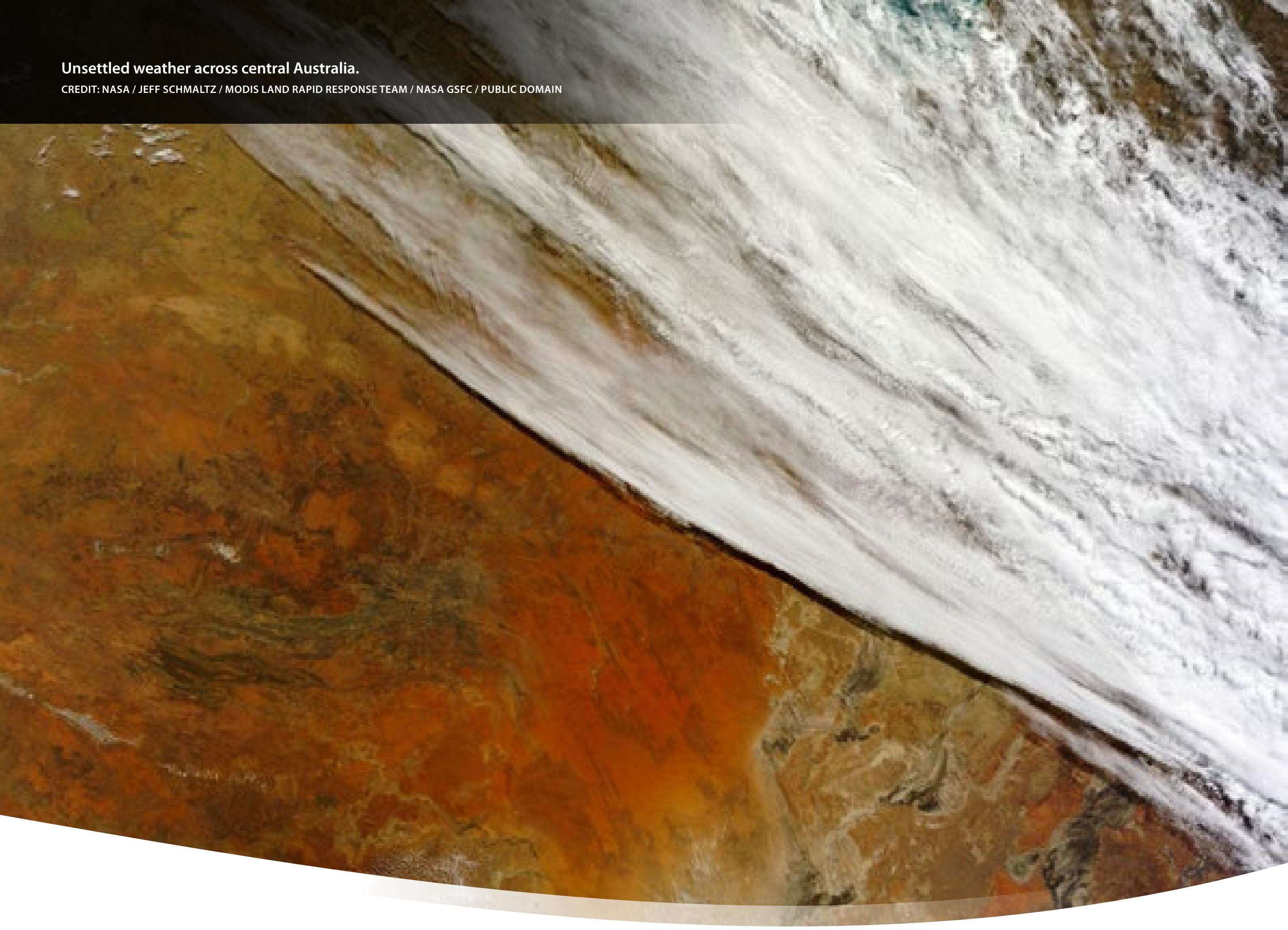
Copper and cobalt exemplify some of the issues we face if we do not generate the knowledge needed to explore successfully in the covered areas of Australia.

The relatively small size of renewable-energy electricity generators and their intermittency means we require about four times as much copper per unit of electrical energy generated compared with a conventional thermal-powered plant. There is a strong move to electric cars and so we will require much greater amounts of electricity. Overall, in the next 15 years we will need as much copper as we have ever used to date. Relative to how much of it we use, copper is geologically one of the scarcest industrial commodities and in the next few years we will be looking at an annual copper deficit almost equal to our current global copper production.

An electric car requires around 65 kg of copper and typically about 10 kg of cobalt. Cobalt currently costs about US$60 000 per tonne.

Bloomberg New Energy Finance (BNEF) estimates that within two decades 16 per cent of cars (that is 282 million cars) will be electric, which equates to about 2.8 million tonnes of cobalt. Set against a current global annual production of cobalt of only about 100 000 tonnes (Australia's annual production is around 6 400 tonnes) it is clear that we will not be able to move en masse to electric cars without an enormous increase in our ability to find and produce cobalt.

Furthermore, 63 per cent of the world's cobalt comes from the Democratic Republic of the Congo and their market share is currently set to rise to 73 per cent by 2025. BNEF estimates that by 2030 global demand for cobalt will be 47 times the demand in 2016 and so, unless we can become self-sufficient in this strategic metal, Australia will be held to ransom with massive price increases and chronic shortages.



Unsettled weather across central Australia.
CREDIT: NASA / JEFF SCHMALTZ / MODIS LAND RAPID RESPONSE TEAM / NASA GSFC / PUBLIC DOMAIN

4.3 Australia's energy future

Safe, sustainable, and reliable energy supply for Australian society is a major challenge with lasting implications for our future well-being. Geoscience research was critical in the discovery of the oil and gas resources which powered the development of our modern society, and so Australia now remains well placed to capitalise on the increasing demand for natural gas in coming years.

Resources required for sustainable energy production are also changing, for example with less reliance on coal and increasing reliance on renewable energy and batteries for energy storage. A forecast from the 2016 World Energy Outlook is that wind and solar will dominate new energy infrastructure over the next 25 years, followed by natural gas. Since such technology relies heavily on strategic metals, raising the success rate of mineral exploration for such metals in the covered areas of Australia will be central to securing our energy future.

Australia does not have any conventional hydrothermal energy resources, yet there is immense potential for many types of non-conventional geothermal resources—although they are not uniformly distributed or necessarily aligned with population centres. Large areas of Australia are suitable for the operation of ground-source heat pumps or thermal energy storage in aquifers, each of which can reduce energy use requirements in homes, other buildings, and manufacturing. Some areas have hot sedimentary aquifers that provide a source of low- to zero-carbon energy, either by extracting heat from hot groundwater (e.g. Birdsville) or using the hot water directly (e.g. Warrnambool).

Australia also has deep, non-conventional 'hot dry rock' resources, generally in the Otway, Gippsland, and Cooper–Eromanga Basins of eastern Australia, in which rocks at depth are relatively hotter than similar rocks elsewhere in the world and are covered by (relatively) insulating layers. Previous attempts to develop engineered geothermal systems to harness these resources on a large scale have shown that we require much better knowledge of Australian sedimentary basins and the deep Earth.

Australia has vast resources of unconventional gas including coal-seam gas, shale gas, and tight gas. But the gas is found in complex geological systems and can be difficult to produce, requiring innovative technological solutions for extraction. Hydraulic fracturing is often used to increase gas flow. If not properly informed by geoscientific input and adequately managed, the production of unconventional gas presents potentially significant environmental consequences such as fugitive emissions, significant use of water, and risks to groundwater systems. According to the Department of

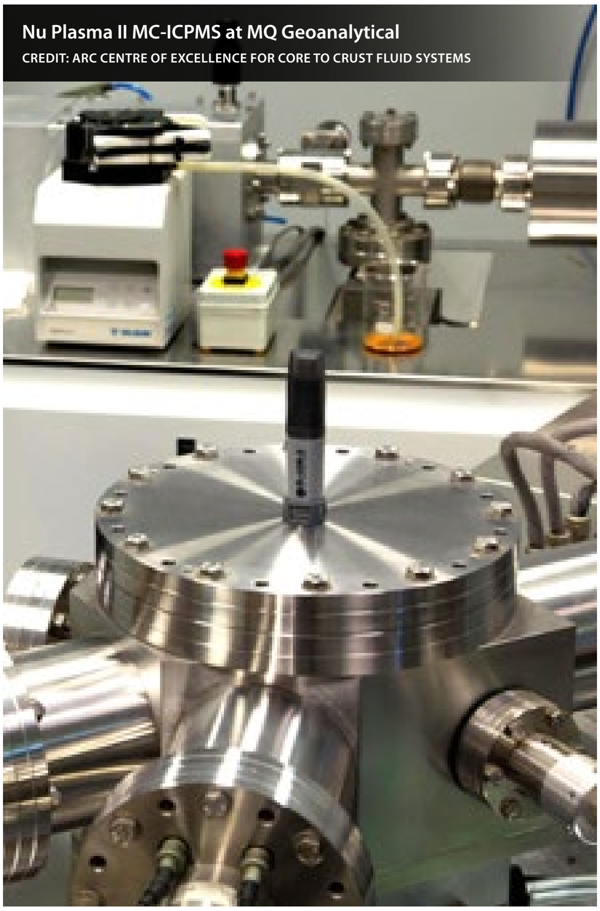
Copper, Boddington Gold Mine, Western Australia.
CREDIT: FLICKR / JAMES ST. JOHN / CC BY 2.0

Copper coils are essential to a range of modern technologies.
CREDIT: FLICKR / MATTHEW VENN / CC BY-SA 2.0

Environment's latest estimates (2012–13), fugitive emissions from the fossil fuel industry account for 8 per cent of Australia's national greenhouse gas inventory. Advances in geo-engineering and geoscience will improve the safety of unconventional gas extraction, and improvements in communication of this knowledge will give communities a better basis for decisions about this resource.

Australia also has rich uranium and thorium resources, and large areas of stable ground potentially suitable for safe radioactive waste storage. As we strive towards a sustainable energy future, it is important to continue the community conversation on all energy sources, including nuclear energy. Again, it is the responsibility of geoscience to develop and communicate sound technical knowledge, allowing future debate to be well informed and wise choices made.

These changes provide new opportunities for Australian enterprises, although each must be both economically and environmentally viable. New research on these resources must be underpinned by a robust scientific understanding of each resource, how it can be used for the greatest sustainable benefit, and factors that may affect social acceptability.



Nu Plasma II MC-ICPMS at MQ Geoanalytical
CREDIT: ARC CENTRE OF EXCELLENCE FOR CORE TO CRUST FLUID SYSTEMS

4.4 Geohazards

The tectonic processes that control Earth's surface—such as plate motion, subsidence, sea level variation, tsunamis, earthquakes, and volcanism—pose significant risks for humanity. Understanding these dynamic forces, both temporally and spatially, relies on effective monitoring and will enable us to better manage these hazards.

The Australian Plate is generally considered to be relatively stable, and as a result geohazards such as earthquakes tend not to be front-of-mind for the majority of the population. However, the Plate is under high stress, has a history of strong seismicity (e.g. the rupture of the Cadell Fault 25 000 years ago, estimated at greater than magnitude 7), is subject to smaller, shallow damaging events (Newcastle 1989: magnitude 5.6, 13 fatalities, $4 billion damage), and is surrounded by plate boundaries in Indonesia and the Pacific capable of generating very damaging tsunamis.

Geohazards will become more devastating as the global population increases and the built environment expands its footprint. Improved knowledge of the underlying mechanics of deep Earth and surficial processes is required for better forecasting of the risks and hazards and better mitigation of their impacts.

Mitigation of impacts has been improved by integration of geohazard science with cutting-edge communication warning technologies. These systems are also effective in addressing and mitigating the impacts of other hazards such as bushfire, floods, or terrorism.

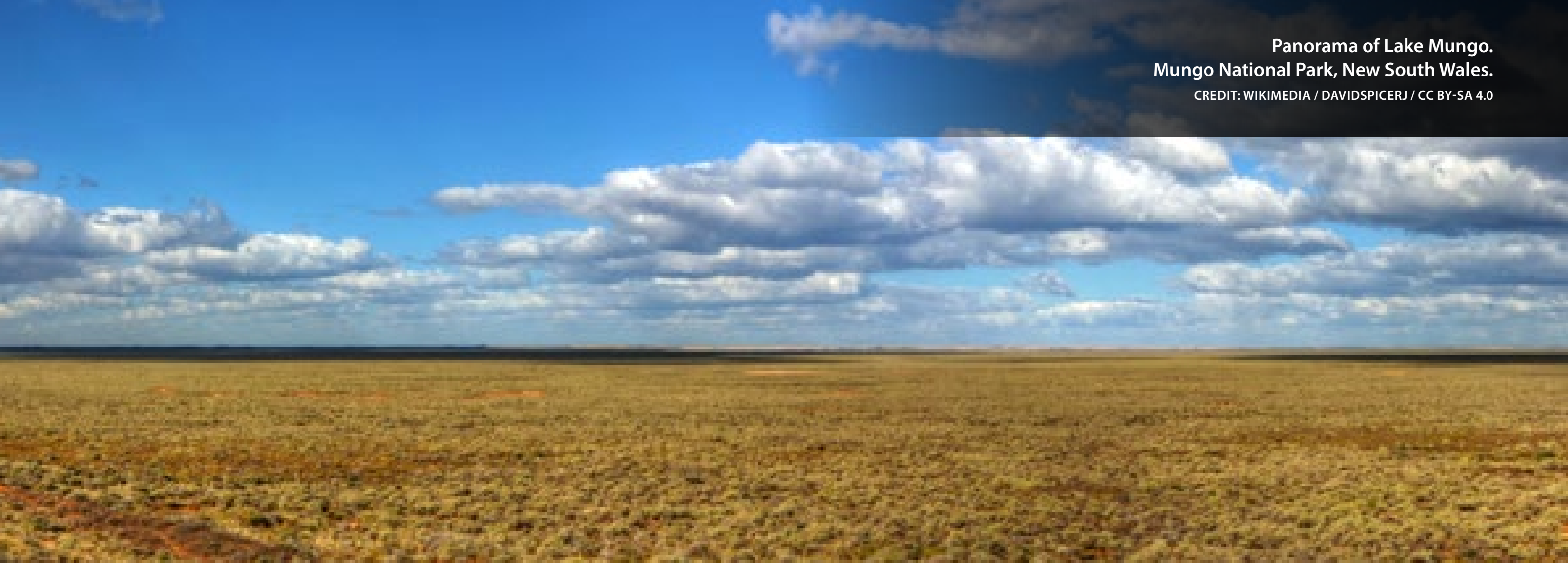
Resilience to changing climate and environmental processes is also vital to our future. More than 8 out of every 10 Australians live within 50 km of the coast, making Australian society highly sensitive to sea-level changes.

Geoscience has provided an in-depth analysis of past climatic variation, knowledge which is essential for understanding disruptions to current and future climate systems and the consequences of these disruptions. It complements research into our Earth's dynamic atmosphere, hydrosphere, and cryosphere; it also underpins our understanding of climate change, as well as informing adaptation and mitigation strategies. Burial sites uncovered at Lake Mungo in 1969 revealed that the area was continuously occupied through periods of radical climate and environmental change; the first Australians offer an important wealth of knowledge regarding change and adaptation.

A river of smoke more than 25 kilometres wide flowed southeast toward the Tasman Sea from fires burning in the Great Dividing Range Mountains in Victoria, on December 5, 2006.
CREDIT: NASA / MODIS RAPID RESPONSE TEAM / GODDARD SPACE FLIGHT CENTER / PUBLIC DOMAIN

It is not just human societies that depend on the well-being of the planet. To preserve and maintain regions of significant natural heritage, it is important to understand the biodiversity of terrestrial and marine environments and how they are shaped by geological processes both onshore and offshore.

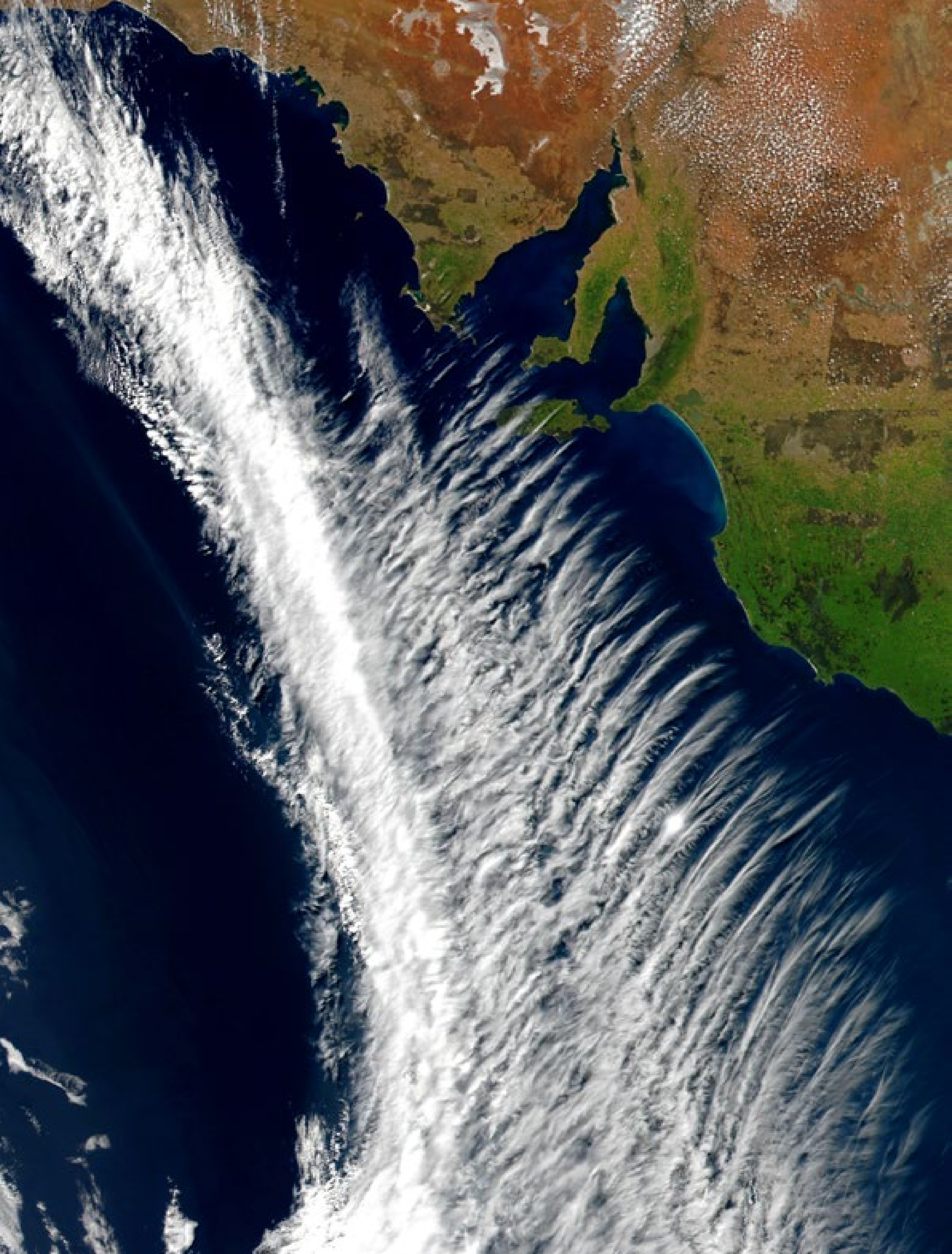
Geoscience must grow and change in the coming years. To respond to these key challenges, it must reach a holistic perspective which is both wider and systems-based.



Panorama of Lake Mungo.
Mungo National Park, New South Wales.
CREDIT: WIKIMEDIA / DAVIDSPICERJ / CC BY-SA 4.0

SciScouts (the next generation of geoscientists) recording a 'footquake' in Canberra in August 2017.
CREDIT: SIMA MOUSAVI / AUSCOPE / AUSTRALIAN SEISMOMETERS IN SCHOOLS PROGRAM AT ANU

Researchers engage in a 3D visualisation of tectonic plate subduction simulation at Monash University.
CREDIT: AUSCOPE / PROF. LOUIS MORESI AND OWEN KALUZA



Unusual cloud pattern off the coast of South Australia near Kangaroo Island.
CREDIT: NASA EARTH OBSERVATORY / JOSHUA STEVENS / PUBLIC DOMAIN

5 Achieving a predictive capability

"THIS WILL ONLY BE ACHIEVED THROUGH AN INTEGRATED, COMPLEX-SYSTEMS APPROACH BUILT AROUND AN INNOVATIVE RESEARCH PROGRAM."

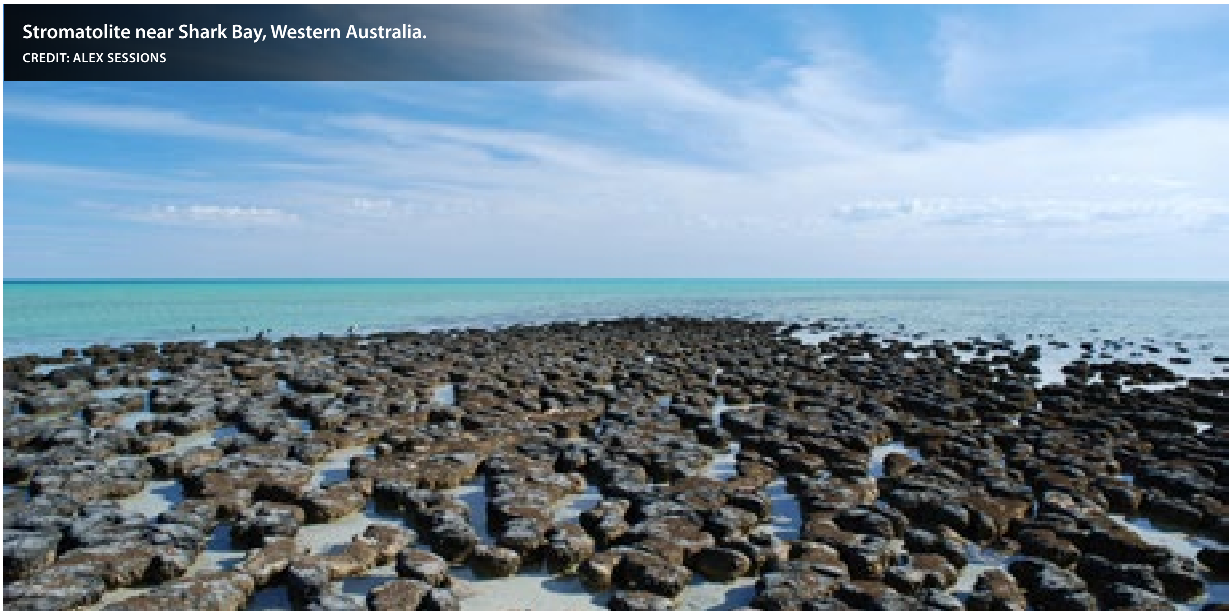
The overarching challenge for geoscience in the coming decade is to create a predictive framework for how our planet will behave, how it will respond to the increasingly intense demands we make on all the services it provides, and how and where to explore for the critical resources we need to underpin our future. In short, how to access and make responsible use of minerals and energy, water and soils, and habitable land, while minimising the impact on the dynamic characteristics of our planet.

This will only be achieved through an integrated, complex-systems approach built around an innovative research program. In addition, it will also be necessary to have infrastructure that is able to provide new ways of looking down into Earth. To interrogate and understand the data flowing from such tools, high-powered data and computational capabilities will be needed, together with international collaboration. All this must be underpinned by an education system that not only can reinforce traditional skills in geology, geophysics, geochemistry, and geodesy but can also expand those skills into new technologies and data or computational capability. Because of the breadth of the challenge and the skills required, we must ensure better translation and integration into the broader scientific community. This includes ensuring that physicists, chemists, mathematicians, biological scientists, and computational and data scientists recognise that geoscience provides satisfying career opportunities.

Extensive commentary on the required program is provided in a companion document[15], so only brief commentary is provided here and the companion document should be read for completeness.

Siphon irrigation of cotton near the Balonne River, St. George, Queensland.
CREDIT: WIKIMEDIA / HULLWARREN / CC BY-SA 3.0

15 https://www.science.org.au/support/analysis/decadal-plans-science/decadal-plan-australian-geoscience



Stromatolite near Shark Bay, Western Australia.
CREDIT: ALEX SESSIONS

5.1 Research

Maintenance of research strength in traditional geology, geochemistry, and geophysics is vital, as this provides the primary capacity to 'read the rocks' and understand Earth processes from core to crust throughout deep time. In the coming decade, this research must be supported and augmented by new technologies, and massively increased capacity and capability in data and computational power. In addition, we need better simulation and modelling, with artificial intelligence methodologies to guide acquisition of national datasets. Geoscience must draw in as much new capability as possible from associated STEM disciplines.

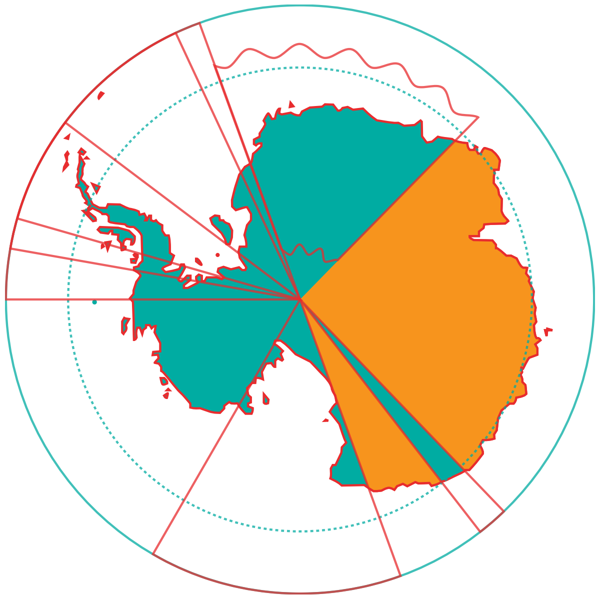
ARC grants are the lifeblood of much of Australia's geoscience research. We applaud the proposed introduction of a national impact and engagement assessment process, currently being piloted by the ARC, as this will encourage greater collaboration between researchers and the many industries underpinned by geoscience. The ARC has been grappling with the difficult issue of how to rank multi- and inter-disciplinary research grant applications which address complex-system questions; we encourage the ARC to continue to improve this process as it is vital to geoscience. We also encourage the ARC to consider an assessment criterion that takes into account community determination (such as through the UNCOVER Australia initiative) of priority areas for research. However, these changes should not come at the expense of the ARC's ability to independently assess and maintain the quality of the research it funds.

Earth sciences in general face the issue that we cannot re-run the planetary and continental evolution 'experiment' many times to help us understand the processes more deeply. Our planet is just one outcome of all the possible ways it could have formed, and the continent of Australia is just one possible continental outcome. Hence, to be able to properly understand our continent and its evolution, it is necessary to study parallel circumstances and analogues elsewhere in the world and to engage in planetary studies, particularly of the other terrestrial planets (the rocky planets Mercury, Venus, and Mars).

Australia is home to the oldest living culture on Earth, which has witnessed periods of great change (such as sea level fluctuations and volcanic activity). There is much to be learned about, for example, Earth systems, ecology, geomorphology, and land management. This is a research opportunity for two-way knowledge transfer that must not be wasted.

Geological and geochemical signs of life on early Earth are extensively distributed across the globe and we must continue to investigate the origins and evolution of life on Earth as it deepens our understanding of life today. The Australian continent has provided extraordinary evidence of early life—such as the Ediacaran fauna in South Australia, the stromatolites in Western Australia, and the oldest known minerals on the planet (zircons in the rocks of the Jack Hills Range, Western Australia)—and so this country offers ideal field sites to probe such questions.

It has long been known that biological agents were critical in the creation of our fossil fuels and ore deposits such as banded iron formations. It is now recognised that microbes are pervasive in driving fundamental biogeochemical processes, both on the surface and at a range of depths within our planet (including mediation of the global cycling of carbon and other nutrients, biomineralisation processes, and bio-alteration or remediation of polluted sites and landscapes). These biological processes are central to maintaining a stable and habitable planet. Greater effort must go into geobiology, employing molecular biology, environmental biology, genomics, and organic geochemistry of the geological record to investigate the evolutionary synergies of life and the inorganic Earth.



Antarctica, with Australia's territorial claims shown in orange.

CREDIT: WIKIMEDIA / LOKAL_PROFIL CC BY-SA 2.5 HTTPS://COMMONS.WIKIMEDIA.ORG/WIKI/FILE:ANTARCTICA,_AUSTRALIA_TERRITORIAL_CLAIM.SVG

A massive crack forms across Antarctica's Pine Island Glacier.

CREDIT: NASA / PUBLIC DOMAIN

Quaternary studies and understanding neotectonics have been a critical component of our ability to understand our relationship with the surface of the planet and to mitigate the impact of geohazards. Now that human activity has become a significant geological agent (as witnessed by the Anthropocene), intensified research is necessary to identify the Earth phenomena that are anthropogenic and to help understand the consequences. For example, changes in sea level have implications for coastal dynamics and geomorphology, and for the habitability of our coastlines where most Australians live, so we must improve our understanding of the dynamics of the Antarctic ice sheets, Antarctic sea ice, and post-glacier uplift. Geoscience has shown that the current rate of climate change is unprecedented, and we should continue to contribute to climate science by establishing the rate and trajectory of change, with an appreciation of changes that are either driven by natural variability or anthropogenically.

It is important to focus on critical times in Earth's history—the Paleocene–Eocene Thermal Maximum, the Quaternary, the Holocene—to generate records that fill the gaps in existing knowledge of natural climate change. This will require close collaboration with Earth Systems Science, including the Future Earth initiative, so that robust geoscience evidence and knowledge can fully inform research directions and adaptation/mitigation strategies. This will require the development of measurement techniques to track and predict the response of Australia's landscape to climate change in the context of increasingly frequent extreme events.

Geoarchaeology can provide insights into the impact of humans on changing vegetation patterns. It can examine the result of long-term land management practices and, together with other geoscience techniques, has shed light on the activities of early European visitors to the continent, helping to understand and contextualise the rapid changes witnessed since their arrival.

Ongoing research into satellite observations and technologies such as inSAR can greatly improve our understanding of Earth processes. For example, over the past decade AuScope has transformed geodesy into a fundamental capability of geoscience and at the same time has helped promote Australia's geospatial industry.

Approximately half of Australia is covered by sedimentary basins. These basins host energy- and mineral-resource systems and encompass fertile agricultural land, generating much of Australia's economic wealth. The nature and dynamics of complex basin systems affect our ability to use these vital resources sustainably. We need to understand, map, and quantify the many resources they host, to identify the most important geological constraints, be it for mining, energy extraction, water extraction, or farming and to understand the interconnectedness of surface, shallow, and deep systems. For example, more reliable estimates of the impact of coal-seam gas extraction on groundwater systems may help with environmental management, economic forecasting, and the social licence required for the industry to operate.

Ancient weathered landscape of the Pilbara, Western Australia.
CREDIT: GEOSCIENCE AUSTRALIA

Australia has many potentially oil- and gas-rich sedimentary basins, both onshore and offshore, which are underexplored and untested. We can reduce the technical risk associated with their exploration and production by revolutionising our understanding of:

- Geodynamic processes and basin evolution
- Stratigraphic and geographic distribution of source rocks and the types of fluid they produce (oil, gas, or condensate)
- Better prediction of reservoir properties
- Improved prediction prior to drilling through enhanced geophysical techniques.

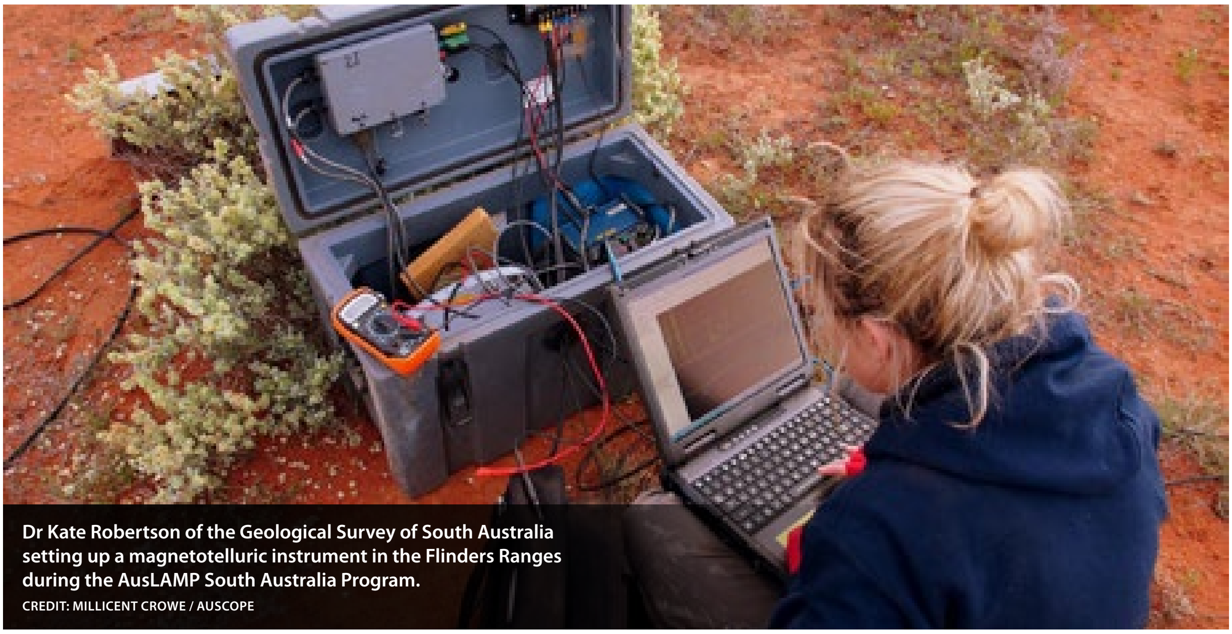
A thorough 4D geochemical and geophysical understanding of our continent is a prerequisite for predicting the existence and location of likely mineral deposits, to robustly forecast and prepare for geological hazard events, and to understand our continent in the context of the whole Earth and of our planet within the solar system.

We need a greater understanding of how Earth has evolved through deep time, delivering virtual visibility of the deep structure which forms and supports Australia. Building this knowledge of the physical and chemical systems of Earth will bring success in tackling a range of fundamental challenges.

This will require significant investment in data management and computational capability to facilitate intensive simulation and modelling; it will also need significant investment in observational infrastructure and nation-wide data acquisition programs to provide the necessary data.

Fully understanding the regolith—including the microbes and other biological inhabitants of the system—and its relationship to the solid crust is important for ensuring the security of a variety of resources, be they soils, water, minerals, or energy. As our knowledge of the solid Earth expands, we are beginning to realise far more synergy and mutualistic relationships with the biological world in many of the fundamental processes.

Understanding the upper 500 m of our continent is key baseline information for a range of important issues: mineral exploration (both strategic non-bulk metals and high-quality iron ore), onshore gas extraction, and geological aspects of agriculture, livestock, and water quality. Acquiring this knowledge will require concerted efforts in understanding 4D landscape evolution, weathering history, and critical zone development. It will require an integration of weathering history, palaeoclimatic history, conductivity and magnetics of rock, sedimentology, stratigraphy, and biological processes. It will need to be supported by a national-scale 3D geochemical survey, combined with hydrogeological studies to understand chemical mobility through time.



Dr Kate Robertson of the Geological Survey of South Australia setting up a magnetotelluric instrument in the Flinders Ranges during the AusLAMP South Australia Program.
CREDIT: MILLICENT CROWE / AUSCOPE

Approximately two-thirds of the area of Australia and its territories is over the sea, and this marine territory brings both responsibilities and opportunities. Marine geoscience was critical in formulating the concept of plate tectonics, a prime example of how marine geoscience is central to our understanding of Earth processes. Marine geoscience provides the essential context for continental geoscience, and deals with regions which have significant energy and mineral resources. Ongoing support for marine geoscience is therefore imperative in the coming decade.

Among other endeavours, it is important to investigate the dynamic interplay between Earth's oceans, its climate, and the Australian continent (much of which actually underlies our oceans). We also need to investigate our marine continental slopes and shelves, ocean-margin sediments, crustal systems, and oceanographic factors that affect these environments. We need to investigate sediment dynamics on Australia's coastlines, estuaries, and near-shore environments (including the Great Barrier Reef), how these will be affected by rising sea level, and the implications of development and urbanisation. Interaction with the NCRIS Integrated Marine Observing System (IMOS) facility, the Australian Antarctic Division (AAD), and other marine science organisations such as the Australian Institute of Marine Science (AIMS) will be vital to achieve the necessary integrated understanding. Much of the required geoscience will not be possible without ongoing access to IODP.

Roughly 70 per cent of our continent's bedrock remains seriously under-explored because the cover defeats current exploration methodologies. New knowledge about our continent, appropriately targeted, is needed and this presents a unique and exciting opportunity with potentially enormous payoffs.

The current UNCOVER Australia initiative is designed to generate breakthroughs in geoscience that will lift mineral exploration success in the covered parts of Australia up to the levels that, two to three decades ago, were previously enjoyed in the uncovered areas. UNCOVER Australia is a collaboration between industry, government, and academia to identify and prioritise the sort of science required to break the barrier that cover presents; it seeks to re-establish Australia as a preferred greenfield mineral exploration destination. The initiative is run under the aegis of the Australian Academy of Science, is strongly endorsed by the Australian Academy of Technology and Engineering, and is embedded in the National Mineral Exploration Strategy released by the COAG Energy Council. It is a template for how fundamental and targeted science can actively assist Australian industry. Although UNCOVER Australia may evolve over the coming decade, it provides a robust foundation for a decade of transition in Australian geoscience.

Exploration drilling can provide geological surveys with valuable information regardless of immediate commercial outcome that will benefit Australian industries in the longer term.
CREDIT: GEOSCIENCE AUSTRALIA

UNCOVER Australia embodies the complex-systems approach needed to enhance geoscience's predictive capability. It will require access to world-class infrastructure and will depend on science of the highest possible quality in all areas of geoscience and in related fields.

Success in this enterprise will give Australia immediate access to the strategic metals needed to develop the future we want: renewable energy, electric cars, rare-earth metals for commercial, industrial, and military technology, a healthy METS sector, and a significant export capability. Failure will mean that Australia could be held to ransom by other countries for access to these resources: instead of funding our future through exports we will have to find the money to import these essential commodities.

At the highest level, the envisaged research program requires some essential ingredients: the understanding of mineral systems and mineral footprints across a multitude of scales; understanding geochemical migration and dispersion of elements through post-mineral cover; full characterisation of the cover to expose scale-dependent exploration signatures; new maps of mantle-to-crust 3D architecture; and 4D geodynamic metallogenic maps of the whole Australian continent.

This will require concerted research input from almost all branches and aspects of geoscience; the field will revolutionise our understanding of the Australian land mass from the deep Earth to the top of the crust. Prosecuting this agenda will create new technologies and knowledge that will have far-reaching implications beyond the minerals sector. Thus, although the initiative is first targeted at mineral exploration to provide a strategic focus, it will drive a broad range of fundamental research, continually producing new knowledge and indeed requiring it in return.

Given the importance of re-establishing Australia as a preferred destination for global exploration activity, and the urgency of providing effective knowledge to the exploration industry, it is a national imperative that this strategic initiative be nurtured and supported.

A detailed roadmap for achieving the objectives of the UNCOVER initiative, 'Unlocking Australia's hidden potential: an industry roadmap', was recently published by AMIRA International.

The Great Barrier Reef captured using a multi-angle imaging spectroradiometer.
CREDIT: NASA / GSFC / LARC / JPL / MISR TEAM / PUBLIC DOMAIN

The Pinnacles, Nambung National Park, Western Australia
CREDIT: WIKIMEDIA / BINARYSEQUENCE / CC BY-SA 3.0

A trio of CubeSats moments after being ejected from a small satellite deployer outside of the International Space Station's Kibo lab module.
CREDIT: NASA / PUBLIC DOMAIN

5.2 Infrastructure

Infrastructure, both at the ARC Linkage Infrastructure, Equipment and Facilities (LIEF) institutional scale and at the national scale, is central to the geoscience capability over the coming decade.

National-scale infrastructure from NCRIS facilities such as AuScope, TERN, NCI, the Pawsey Supercomputing Centre, BPA, the Australian Microscopy and Microanalysis Research Facility (Characterisation), the Australian National Fabrication Facility (Fabrication), and the Synchrotron are central to the national geoscience capability. It is imperative that support for these facilities continues. This is not just for the sake of growing geoscience but is also crucial for the broad spread of Australian research.

Research infrastructure has a demonstrable impact on the national economy. The net benefit to Australia from investment in research infrastructure by AuScope alone has already been reckoned as approximately $3.7 billion in 2015–16 terms[16]. This impact is spread across fundamental geoscience, resource exploration, the natural and built environment, and spatially sensitive industries.

Advances in information and communications sciences have caused a rapid technological disruption in many sectors. Indeed, the adoption of digital systems and infrastructure has pervaded almost all facets of modern life. Geoscience has already shared in the benefits of the information revolution: cheaper processors of increasing capacity have allowed more complex and realistic models; there is now ready access to satellite data; geophysical and geochemical models are now data-rich; results are communicated faster; and there is greater capacity and mechanisms for collaboration.

A structural shift in our approach towards integrating tools is required to take advantage of additional capability. The boundaries between disciplines such as geophysics and geochemistry are blurring, and they can no longer be viewed separately.

Geoscience is about to undergo even more radical changes. For example, the next decade will deliver an array of efficient, miniature mobile sensors, coupled with affordable computational power to deliver real-time feedback. Technology to deploy sensors, for example, on Unmanned Aerial Vehicles (UAVs) with extended flight times and on-board target identification is on the drawing boards. Ubiquitous millimetre-precision positioning in the field will be available, leading to fine-scale resolution mapping of everything on, above, or below Earth's surface. Advanced and cheaper computational power will continue to expand the range and nature of data analysis. Better data management and computational capability will improve efficiency even beyond what hardware alone can deliver: machine-learning techniques will extract tangible information from expanses of data with ever-increasing sophistication and efficiency.

The continued development of integrated national research infrastructure platforms, such as AuScope, will provide access to state-of-the-art, field-deployable observational and monitoring capabilities, remote sensing and imaging technologies, and data management, discovery, and delivery systems—in addition to our traditionally strong laboratory facilities.

16 Lateral Economics, 2016. *AuScope infrastructure program: evaluation of impacts. A Lateral Economics report for AuScope Limited.* http://auscope.org.au/wp-content/uploads/2017/02/Lateral-Economics-report.pdf

Case study: Strategic research infrastructure provides the platform for world-class geoscience research

AuScope developed and currently manages an integrated National Earth and Geospatial Sciences Research Infrastructure (NEGSRI) system as part of NCRIS. The investment provides an array of new observational and monitoring instruments, and an eResearch platform provides tools for data management and discovery, vocabularies, and data standards for providing interoperable data across the country. A series of simulation modelling and analytical tools adds value to these datasets.

One of the significant successes of these programs has been the development of national Global Navigation Satellite Systems (GNSS) coverage in collaboration with Geoscience Australia. Farmers, climate scientists, and surveyors all need detailed and accurate measurements of the changing Australian continent. AuScope contributed 55 GNSS stations to a network of 101 stations around the country, placed about 200 km apart. The network can accurately pinpoint shifts in the Australian continent. Along with an advanced GNSS network, AuScope also operates three radio-telescopes for Very Long Baseline Interferometry (VLBI) to measure deformation of the Australian continent. AuScope's infrastructure provides accurate data for applications in a host of industries.

Investment in strategic infrastructure has revolutionised the type and quality of data available for Australian geodesy researchers and has transformed geodesy into a core capability of Earth Science. It provides a significant and measurable return on investment in the Spatially Sensitive Industries sector[17].

Over the next decade, AuScope will invest in an Australian Earth Observing System (AEOS). AEOS will support the development of the downward-looking telescope described in the Chief Scientist's 2016 National Research Infrastructure Roadmap[18] through the provision of new observational, remote sensing, and monitoring infrastructure. Perhaps more critically, AEOS will revolutionise the way Earth scientists interact with national datasets—in much the same way that investment in GNSS revolutionised Australian geodesy research over the past decade.

eResearch infrastructure will provide national 3D datasets linked from the point of sampling in the field to the eventual publication of data or research papers using IGSN identifiers. It will embed the FAIR data principles[19] into Australian Earth Science to increase the enduring value of the data. This development will also provide a framework for close collaboration to develop discipline-independent national datasets and data formats through collaboration with capabilities such as IMOS, TERN, NCI, the Pawsey Centre, Geoscience Australia, CSIRO, and the Australian Bureau of Meteorology (BOM).

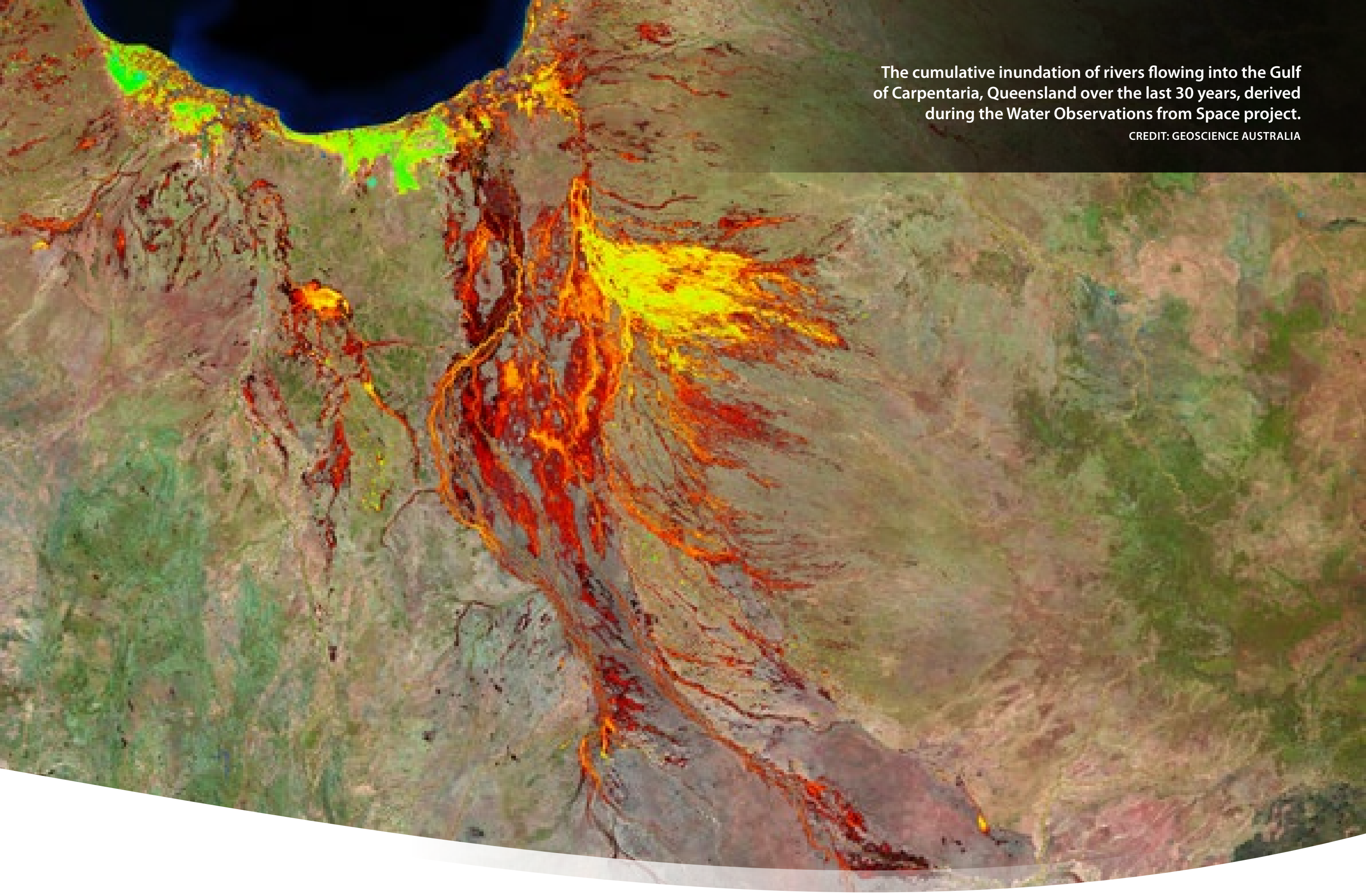
NASA's Global Hawk being prepared at the Armstrong Flight Research Center, USA, to monitor and take scientific measurements of Hurricane Matthew in 2016.

CREDIT: NASA / LAUREN HUGHES / PUBLIC DOMAIN

17 Lateral Economics 2016: http://auscope.org.au/wp-content/uploads/2017/02/Lateral-Economics-report.pdf

18 Department of Education and Training: 2016 National Research Infrastructure Roadmap: https://docs.education.gov.au/node/43736

19 FAIR: Findable, Accessible, Interoperable, and Re-usable—see doi:10.1038/sdata.2016.18



The cumulative inundation of rivers flowing into the Gulf of Carpentaria, Queensland over the last 30 years, derived during the Water Observations from Space project.
CREDIT: GEOSCIENCE AUSTRALIA

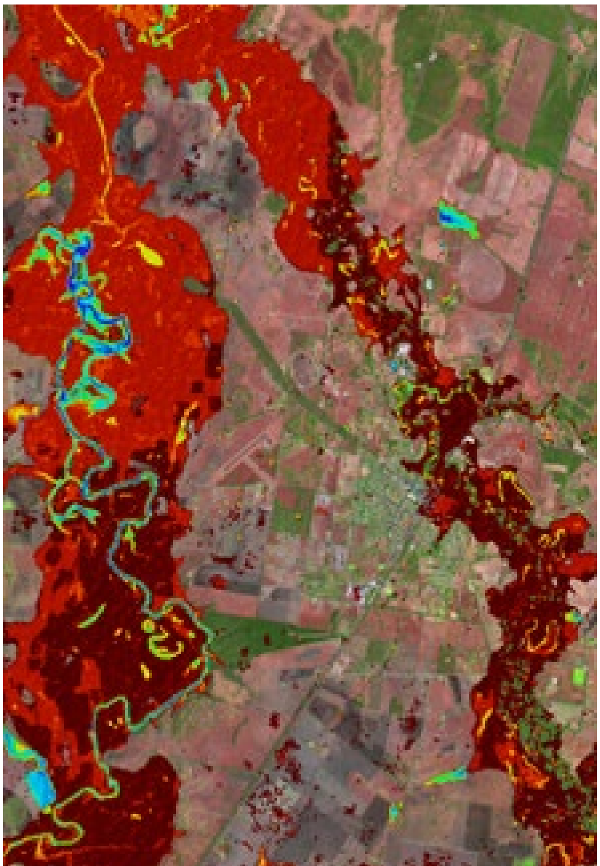
5.2.1 Enhanced observational capability

To achieve the necessary predictive capability and to prosecute the UNCOVER initiative successfully, geoscience needs continent-wide observations at a spatial resolution higher than we currently have, and this must apply to both current and new sensors.

The 2016 National Research Infrastructure Roadmap identified, as a priority, the establishment of next-generation Earth monitoring infrastructure and the development of a 'downward-looking telescope'. This technology will provide a distributed observation network which will help us understand the workings of our landscape and how it controls our resources, energy, agriculture, food, natural hazards, and responses to environmental change. More fundamentally, it will help us understand deep Earth processes, which is one of the goals of the UNCOVER initiative.

Over the past decade the NCRIS AuScope facility has proven to be enormously effective in creating and managing infrastructure for the geoscience research community. It has been seminal to a multitude of research programs and is now central to the health of Australian geoscience. Responsibility for operation and management of infrastructure for a downward-looking telescope should reside with AuScope.

Observational capability in marine geoscience is underpinned by the infrastructure platforms provided by IMOS and the IODP. It is imperative that Australia maintain its subscription to this program.



Water Observations from Space project results over Chinchilla in southern Queensland showing neighbouring rivers occasionally flooding enough (red areas) to inundate the town itself.
CREDIT: GEOSCIENCE AUSTRALIA

Elements of a downward-looking telescope

A distributed network of geophysical and remote sensing deployments, together with a geochemical sampling program, consistent with the UNCOVER initiative

- Acquisition and deployment of geophysical instrumentation to collect high-spatial-resolution geophysical data across a range of methodologies: seismic (passive, ambient noise), electrical, gravity, magnetic, and other techniques that become available. The overall aim is to probe the Australian lithosphere (continental, marine, and territories) to depths of at least 300 km
- Remote monitoring of the Australian continent using satellite technology
- Geochemical-tomography surveys of Australia (and its marine surroundings and Antarctic territories where practical) at depth slices from 1 to 300 km, integrating geophysical, geochronological, geodetic, and geochemical datasets. This will include: use of available heavy mineral concentrates and new sampling campaigns in high-priority regions; hafnium isotopic mapping using zircon and other relevant minerals from heavy-mineral concentrates; and selective use of mineral separates from rock outcrops for prioritised ground truthing
- 4D integration of geoscience datasets in a consistent digitalised environment to interpret the structure and composition of the Australian continent in different depth- and time-slices.

An Australian Earth observation system using space technology

- Conduct targeted and sustained environmental, geological, and geophysical monitoring to provide national-scale datasets that will inform evidence-based mineral exploration and management strategies
- Maintain, unify, and, where necessary, augment and fill-in the national network of GNSS reference stations.

A new generation national collaborative geochemical analytical and experimental capability

- Establish and maintain a geochemical and experimental capability based on a collaborative and nationally accessible array of new generation instruments. The facility will expand and enhance the in situ approach to trace-element and isotopic analyses originally pioneered in Australia, and provide mineral imaging at the nano- to micro-scale. It will develop new techniques and methodologies for in situ geochemical analysis and imaging that will encompass secondary minerals, textures, and structures. It will be able to study biological and chemical reactions at low and high temperatures, mimicked in laboratory environments to simulate real-world examples
  - Extend to the analysis of biological samples
  - Extend experimental capabilities to include simulation of deep Earth conditions, to understand energy and mass transfer from the mantle to the crust, and its role in metallogeny
  - Liaise and innovate with manufacturers to develop new and improved purpose-designed geochemical analysis instruments for export
  - Develop and promote the aggregation of mineral and geochemical databases, including geochronology of Australian mineralised systems and major tectonic episodes.

5.2.2 Data

As with most science today, data are core infrastructure for geoscience. Well-coordinated, strategically-targeted, national-scale datasets with common standards are central to our ability to become truly predictive and solve key geoscience challenges.

Government agencies such as Geoscience Australia and the state geological surveys have supported the minerals exploration industry and much of Australia's geoscience research by providing national-scale geo-data sets. The central importance of these agencies and their activities will continue for a long time. The nationally agreed priorities now available through the UNCOVER initiative provide an opportunity to strategically guide these data acquisition programs. These programs will allow seamless access and integration of data, helping the development and adoption of national data standards and workflows across the geoscience community, either for geoscientific data compilation, acquisition, or storage.

Australia has typically focused more on gathering national-scale geophysical data than geochemical data. This has left us weak in terms of being able to understand the geological evolution and structure of our lower crust—and deeper into the uppermost mantle and beyond. This needs to be rectified. We need new information layers acquired with novel techniques. This may include a high-resolution national geochemical survey, based on a variety of sample media to provide 'ground truthing', and calibrated with new geophysical techniques that can interpret results in a geologically realistic way. This could then provide the first chemical characterisation of the fundamental substrate for future food supplies, other land use, and extractable resources. This effort should proceed hand-in-hand with the creation of new national and regional geochemical standards for sampling and analysis.

Large amounts of data are generated by publicly- and privately-funded research. A central repository and catalogue is needed to collect, compile, and archive all such geoscience data into a consistent format and make them available to industry and for research. Even the relatively small amount (compared to that held by private companies) of publicly-funded Australian research data is not easily accessible. An investment in data standards, ownership, and warehousing—together with secure, continuing, and accessible archiving—will unlock greater value from existing research and observations. Digital Earth Australia[20] (previously the Australian Geoscience Data Cube), a partnership between Geoscience Australia, CSIRO, and the NCI, is a valuable first step towards the type of capability that will support the future of Australian geoscience.

CSIRO's Data61, formed from the integration of CSIRO's Digital Productivity flagship and the National ICT Australia Ltd (NICTA), is a leading group designed to help Australia lead the world in data innovation. The group is heavily invested in building and refining observational technologies that are both pervasive and persistent.

Blue Mountain Supercomputer, Los Alamos National Laboratory
Los Alamos, New Mexico
CREDIT: WIKIMEDIA / LOS ALAMOS NATIONAL LABORATORY / PUBLIC DOMAIN

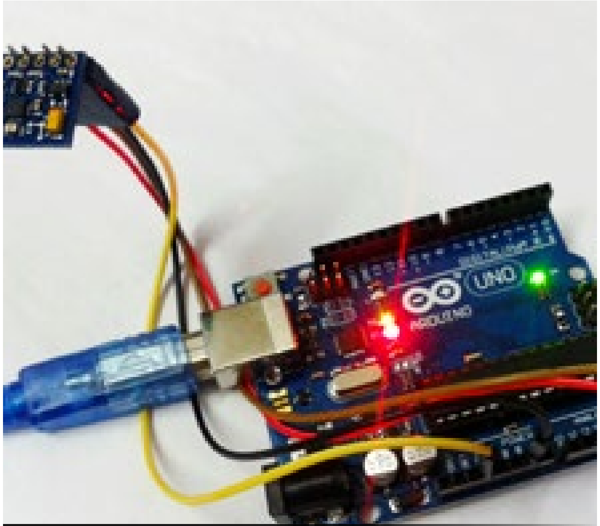
20 Digital Earth Australia: http://ga.gov.au/about/projects/geographic/digital-earth-australia

A generational shift in technology resources and interconnectivity of all facilities is required, including establishment of a virtual laboratory network to enable the sharing of large data (including digitised collections) and the improvement of real-time communication.

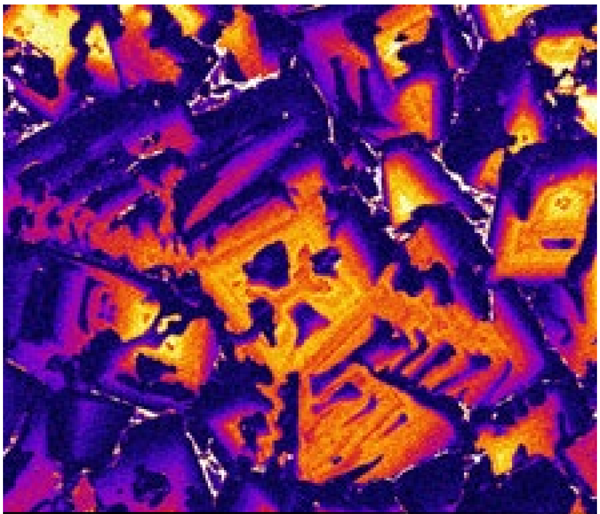
Four issues require specific attention.

- Data repositories: A commitment to, and investment in, the development and maintenance of geoscience-focused research data repositories is critical to supporting the next generation of data-focused research. These should sit alongside traditional national data custodianship infrastructures and focus on supporting maintenance of national research datasets
- FAIR data[21]: all geoscience data, and all publications derived from these data which are publicly available (in particular, data collected or produced through Australian Government and state investment), should be delivered following FAIR data principles: Findable, Accessible, Interoperable, and Reusable. This will facilitate data access and new data-driven research, and is in line with international data accessibility and publishing trends
- National Laboratory Information Management System infrastructure: Geochronology and geochemistry laboratories across the country are beginning to realise the value of linking samples—and the instrumental data captured from them—to datasets, workflows, and publications. Provision of an infrastructure—an integrated national LIMS—will provide an accessible geochemistry and geochronology dataset not available anywhere else in the world
- Collaboration: Membership, or the development of local nodes, of international organisations such as Earth Science Information Partners (ESIP) and Research Data Alliance (RDA) will ensure alignment with international trends in data science and geoscience data management.

Certainty in knowledge of the geology hidden beneath the surface can only be achieved by abundant sampling. That demands an NDI to acquire the final 'ground truthing' data.



Cheap, readily deployed, programmable sensors are set to revolutionise research.
CREDIT: WIKIMEDIA / RAHAT / CC BY 4.0



False colour cathodoluminescence image of corundum crystal ejected from Cretaceous volcanos on Mt Carmel, North Israel.
CREDIT: PROFESSOR BILL GRIFFIN, ARC CENTRE OF EXCELLENCE FOR CORE TO CRUST FLUID SYSTEMS, MACQUARIE UNIVERSITY

Australian inventions such as the sensitive high resolution ion microprobe have had a major impact on global geoscientific research.
CREDIT: GEOSCIENCE AUSTRALIA

21 FAIR data principles: https://www.nature.com/articles/sdata201618

The north face of the National Computational Infrastructure building Australian National University, Canberra
CREDIT: WIKIMEDIA / NICK-D / CC BY-SA 4.0

5.2.3 Computational capability

The computational capacity of the geoscience community is heavily supported by national infrastructure schemes such as the NCI (part of NCRIS) and Western Australia's Pawsey Centre. The existence of such globally competitive computational facilities in Australia is a critical component of the expansion of geoscience into the 'big science' realm. Historically, geoscience has not been a significant player in high-performance computing, but this is set to change. The large overheads in developing and porting code on national-level production-run facilities should be supported through:

- software support and development: for developing, expanding, parallelising, and optimising available geoscience software to make full use of these facilities
- low- and mid-level computing infrastructure: from department-level servers, up to university consortia, which facilitate testing, development, code optimisation, and student learning.

The second avenue is largely supported at a university level, but it needs strategic support from the broader Earth Science community. The first avenue—software development—was supported by the previous NCRIS round under AuScope, and led to the development of software such as Underworld[22], eScript[23], gPlates[24], LitMod3D[25], and various inversion suites[26].

Because the Earth itself is a complex system and many of its components are themselves complex systems, simulation and modelling is absolutely necessary for understanding tsunamis, earthquakes, the deep-Earth processes that generate mineral systems, and 4D geodynamic metallogenic maps of the Australian continent. Ongoing support for accessible national computational capability, such as the NCI and the Pawsey Supercomputing Centre, is imperative.

In this regard, we welcome the injection of $70 million into the NCI announced as part of the 2017 Mid-Year Economic and Fiscal Outlook (MYEFO), and the $70 million for the Pawsey Centre in the 2018/19 Federal Budget. However, in order for Australian science in general, and geoscience in particular, to solve the complex-system challenges that Australia faces, a massive expansion of Australia's national computational capability is required—over and above maintenance of the current capability.

22 Moresi, L, Quenette, S, Lemiale, V, Meriaux, C, Appelbe, B, and Mühlhaus, HB 2007, 'Computational approaches to studying non-linear dynamics of the crust and mantle', *Physics of the Earth and Planetary Interiors* 163(1), 69-82.

23 Gross, L, Bourgouin, L, Hale, AJ, and Mühlhaus, HB 2007, 'Interface modeling in incompressible media using level sets in Escript', *Physics of the Earth and Planetary Interiors* 163(1), 23-34.

24 Williams, S, Müller, RD, Landgrebe, TCW, Whittaker, JM, 2012, 'An open-source software environment for visualizing and refining plate tectonic reconstructions using high resolution geological and geophysical data sets', *GSA Today* 22(4/5), doi: 10.1130/GSATG139A.1.

25 https://eps.mq.edu.au/~jafonso/Software1.htm; Fullea, J, Afonso, JC, Connolly, JAD, Fernandez, M, Garcia-Castellanos, D, and Zeyen, H, 2009, 'LitMod3D: An interactive 3-D software to model the thermal, compositional, density, seismological, and rheological structure of the lithosphere and sublithospheric upper mantle', *Geochemistry, Geophysics, Geosystems* 10, Q08019, doi:10.1029/2009GC002391.

26 Sambridge, M, Bodin, T, Gallagher, K, and Tkalčić, H, 2012, 'Transdimensional inference in the geosciences', *Philosophical Transactions of the Royal Society A* 371(1984), 20110547.

5.2.4 International collaboration

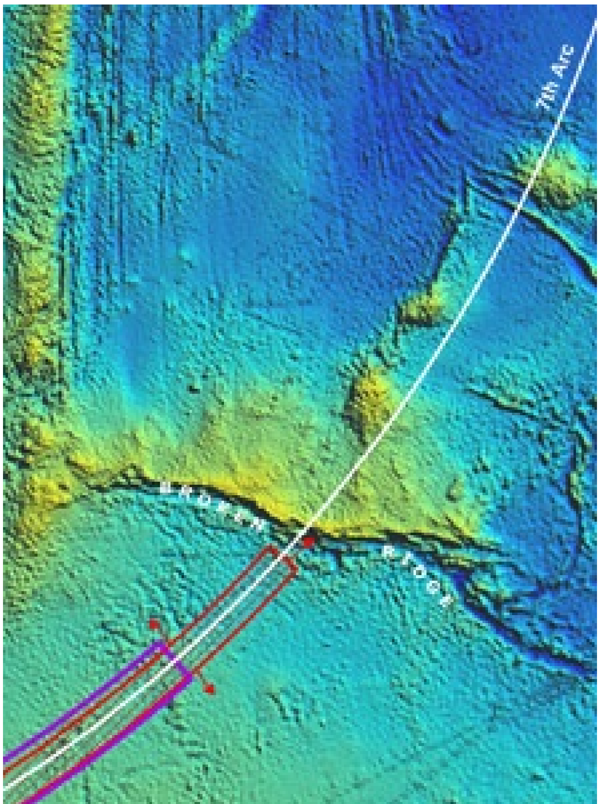
Earth systems extend beyond national boundaries, and collaborations in Earth Science must also extend beyond our own border.

Many questions regarding Australian geology can best be answered by studying analogues on other continents (and *vice versa*), generating global partnerships and collaborations. Similarly, many questions regarding Earth can be informed by studying other planets (the absence of boundaries also virtually assures cooperation).

Collaborations with organisations such as the European Plate Observing System and Earth Cube in the USA will allow Australian Earth scientists to continue their leading role in the development of international geoscience data standards and will be a key to international scientific collaboration.

The ability to access large international infrastructure capability, such as the IODP, is imperative.

Australian Earth scientists need appropriate support to work internationally in the course of their research. Similarly, Australia must be made a desirable destination for international researchers, with ready and reliable access to state-of-the-art facilities, supported by capable and reliable technical staff, secure employment and immigration status while in Australia, and appropriate rights and controls to the data generated.



Map showing progress in 2014 of the underwater search for missing Malaysian Airlines flight MH370.
CREDIT: ATSB / GEOSCIENCE AUSTRALIA / CC BY 4.0

5.2.5 Cross-sector collaborations

The challenges of the next decade will not be addressed by academic research alone. Targeted collaborations must be established between academia, industry, and government organisations to solve problems of common interest. Fully leveraging these different perspectives and capabilities will facilitate the comprehensive approach necessary to tackle the research challenges of the next decade.

Australia needs strategic leadership that coordinates both research and industry efforts, and connects and propels both groups towards a common purpose. This will best be served by an independent body or bodies that sits between industry, government, and academia which focuses on the strategic agenda. The UNCOVER initiative shows this approach is both possible and beneficial.

IODP Expedition 369 Australia Cretaceous Climate and Tectonics returns to Hobart, September 2017.
CREDIT: BRIAN HUBER / IODP

A skeleton of a marsupial lion (*Thylacoleo carnifex*). Victoria Fossil Cave, Naracoorte Caves National Park.
CREDIT: WIKIMEDIA / KARORA / PUBLIC DOMAIN

High school students learning to prepare mineral samples for analysis.
CREDIT: GEOSCIENCE AUSTRALIA

5.2.6 Education

Weakness in Australia's education system for geoscience is a major threat to the ongoing capacity of geoscience to serve the nation effectively.

Falling literacy and numeracy among Australia's school-age cohort will have to be addressed as part of any plan for Australia's future prosperity and international competitiveness.

Geoscience is largely absent in Australia's school system, meaning:

- many decision-makers are not exposed to geoscience and are therefore largely uninformed about the processes, flexibilities, and limitations of Earth as our fundamental life-support system
- most young people entering tertiary education are not acquainted with geoscience, which stops them from recognising that geoscience could be a career.

More secondary students need to be exposed to geoscience, but this is impeded by a lack of teachers with higher qualifications in geoscience[27], coupled to a lack of incentives to entice geoscience graduates to teach. Currently, resourcing and teacher mentoring is only provided in a limited form by organisations such as Earth Science Western Australia[28]. Perhaps the most effective way to overcome this issue is for the professional societies and the National Committee to interact with state governments and curriculum authorities to improve the standing of geoscience in school curricula.

Support for initiatives such as Science by Doing and Teacher Earth Science Education Programme (TESEP; under the aegis of the Australian Science Teachers Association)[29] should be much stronger than it currently is. The National Committee applauds the education programs run by Geoscience Australia and encourages other organisations to support this initiative.

Australian universities today operate as business entities first and educational institutions second. This means that, despite significant Australian Government funding, universities tend to focus on courses that are profitable—that is, of low-cost and with large student numbers. This impacts negatively on STEM subjects in general and on geoscience capability in particular. Many aspects of Australia's future would be improved if the Australian Government recognised that in funding education the money should preferably go to skills that are strategically important for Australia's future wealth, even if only small numbers of graduates are required.

In light of our future need to become significantly more adept at dealing with complex systems, the systems in Australia that support geoscience (and the STEM disciplines in general) need to evolve a more inter-disciplinary approach. This will require national structures that facilitate the development of systemic capability and understanding. Similarly, the approaches taken by the geoscience community in maximising the utility of Australia's resource base need to be improved.

27 Out-of-field teaching is discussed in detail in the *Decadal plan for Mathematical Sciences* (AAS 2016). It is a problem that is shared by geoscience and several other disciplines.

28 Earth Science Western Australia: http://earthsciencewa.com.au

29 Teacher Earth Science Education Programme: http://tesep.org.au

Future graduates need a strong foundation in observational geoscience but also need to be highly capable in accessing new technologies. In particular, geoscience will need increasing numbers of numerate students and graduates.

The evolution of geoscience into a big-data and simulation-intensive field requires the training, education, and nurturing of a computationally literate cohort of undergraduate and postgraduate students who, of course, must also be literate in geoscience.

Geoscience requires the fusing of vast amounts of diverse and incomplete information from a range of sources. This develops skills that are useful across a broad range of careers, particularly in high-level management and decision-making. In essence, training in geoscience is a training for life. Consequently a boost in geoscience graduate numbers benefits the community generally because there is value in having those graduates, not just in geoscience careers, but in decision-making positions throughout society.

The National Committee encourages universities to include a geoscience unit in all first year science degrees to give a broad range of people exposure to understanding our Earth and to experience a discipline that is strongly integrative.

The 34th IGC Travel Grant, operated by the Australian Geoscience Council and the Australian Academy of Science, provides specific funding to Australian and New Zealand geoscientists in the early stages of their careers, giving them opportunities to travel internationally to further their careers. This type of initiative has a powerful long-term impact on the nation's geoscience capability, and the National Committee encourages the creation of similar initiatives that support young geoscientists.

The National Committee recognises the benefit of industry associations such as the MCA for their ongoing funding of NExuS at the University of Adelaide, and the petroleum industry for its support of the Australian School of Petroleum, also at the University of Adelaide. We encourage other associations, professional societies, and industry to provide similar support for geoscience education.

Chrysocolla is a double pseudomorph, formed from malachite which has formed from azurite. Whim Creek Copper Mine, Pilbara Region, Western Australia.

The Organ Pipes, Victoria.

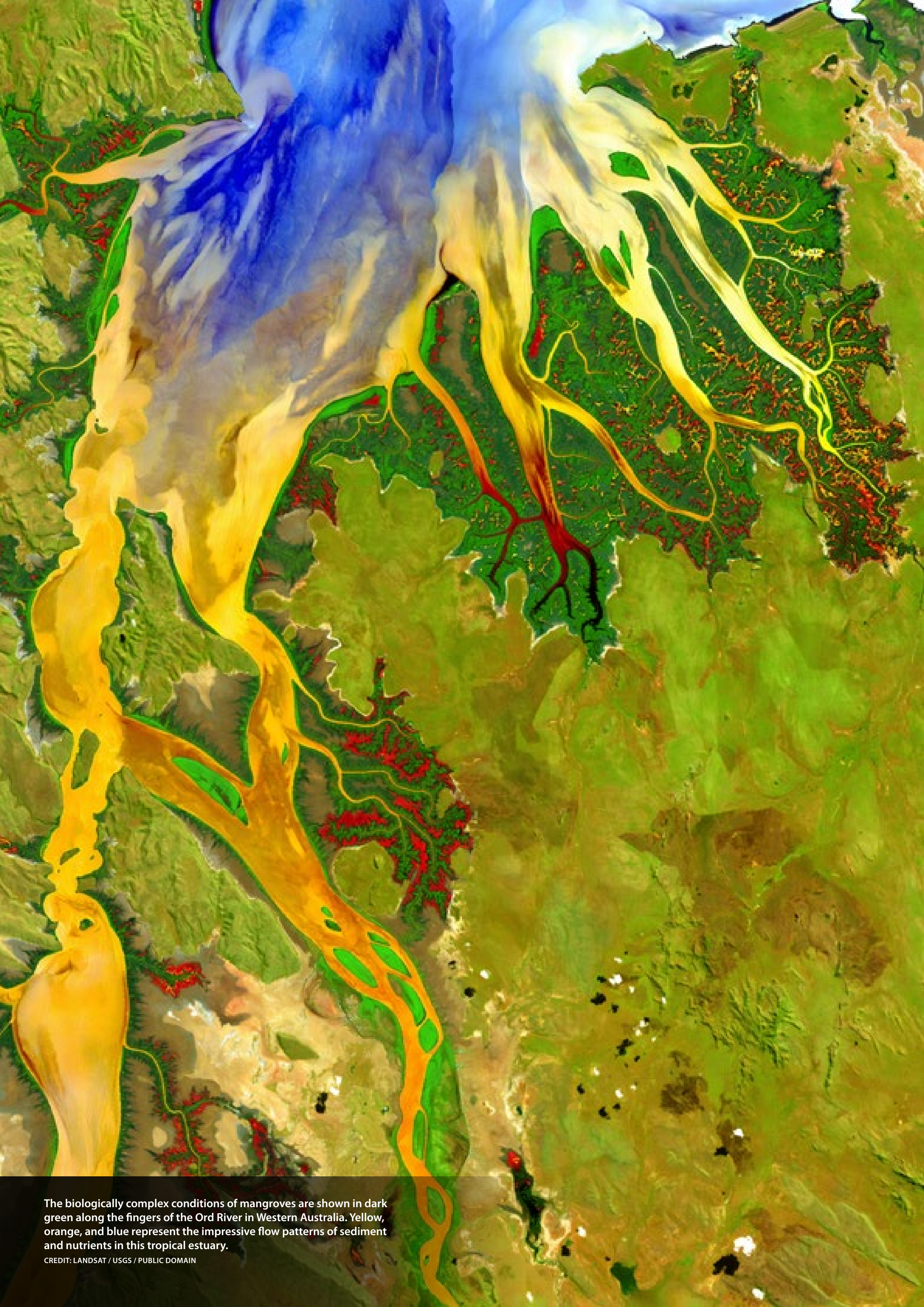
Demonstrating cloud formation to the next generation of geoscientists at a Geoscience Australia open day.
CREDIT: GEOSCIENCE AUSTRALIA

5.2.7 Advocacy

There is a strong imperative for geoscientists to ensure the community understands and appreciates the depth of our dependence on Earth as a life-support system, and on geoscience research to provide the knowledge to responsibly manage our interactions with the planet.

Awareness and understanding of geoscience across the community, including government, thought-leaders, and industry stakeholders, will create a culture that promotes informed debate on complex controversial issues of environmental, cultural, social, and economic importance.

> The story told by our planet is extraordinary—from its birth 4.56 billion years ago to its current state of solid outer shell of continents and liquid ocean on which we pursue our lives. Geoscientists are uniquely placed to interrogate Earth's records and engage the community regarding our society's use of Earth's finite resources. They can enrich human experience, telling of the intrinsic beauty and wonder of Earth. They can convey the message that geoscience is a human endeavour with its own rigour and beauty, while telling us the story of Earth's grandeur, dynamism, and fragility.
>
> This is a particular responsibility for the National Committee and the professional societies, but is also a tale for all geoscientists to tell.



The biologically complex conditions of mangroves are shown in dark green along the fingers of the Ord River in Western Australia. Yellow, orange, and blue represent the impressive flow patterns of sediment and nutrients in this tropical estuary.

CREDIT: LANDSAT / USGS / PUBLIC DOMAIN

6 Recommendations

6.1 Research

1. As a matter of urgency, the Australian Government should support the public-good research agenda of the UNCOVER initiative. Geoscience agencies, institutions, and individual researchers should work together to prosecute and achieve the goals of that agenda, positively impacting the Australian economy

2. The Australian geoscience research community is encouraged to collaborate in a way that will enhance the science's predictive power

3. The Australian Research Council (ARC) is encouraged to pursue the introduction of a national impact and engagement assessment; to continue to improve assessment of multi- and inter-disciplinary research grant applications addressing complex-system questions; and to consider the introduction of an assessment criterion that takes into account community determination (such as through the UNCOVER initiative) of priority areas for research. At the same time, it should maintain strict assessments and maintain the quality of the research they select for funding

4. The Australian geoscience research community is encouraged to:
   - pursue a deeper understanding of the geomicrobiological controls that have affected the Australian continent
   - further investigate the origins and evolution of life on Earth
   - gain a better understanding of the consequences of being in the Anthropocene epoch
   - contribute as broadly as possible to the wider Earth Sciences, such as climate change research
   - provide the research to make informed decisions about competing resource and land use interests
   - become more adept at integrating new technologies and become better at accessing the enormous advantages from advances in data and computational science
   - become more adept at accessing relevant knowledge from all available sources, such as from the first Australians

5. To further investigate the dynamic interplay between Earth's oceans, climate, and the Australian continent, Australian geoscience should:
   - conduct targeted large-scale monitoring and research campaigns, with a focus on the Southern Hemisphere, with specific paleoclimate and paleoceanography targets
   - develop Australian marine research by collaborating with the Integrated Marine Observing System (IMOS), the International Ocean Discovery Program (IODP), the Australian Antarctic Division (AAD), the Australian Institute of Marine Science (AIMS), and other marine science organisations
   - investigate marine continental slopes and shelves, ocean-margin sediments, and the crustal systems and oceanographic factors that affect these environments
   - investigate sediment dynamics on Australia's coastlines, estuaries, and near-shore environments (including the Great Barrier Reef) to understand how these will be impacted by rising sea levels and the implications for development and urbanisation

6. The Australian Academy of Science is invited to consider conducting a 'Theo Murphy Think Tank' investigating the future of energy resources in Australia; such an event would provide a stimulus for considering the value of research into all forms of energy, conventional and unconventional

6.2 Infrastructure

6.2.1 Enhanced observational capability

7. As recommended in the 2016 National Research Infrastructure Roadmap, the Australian Government should fund the creation of a downward-looking telescope to be operated and managed by AuScope. This project would be in addition to other programs within centres of research concentration. The telescope would have a significant impact on geoscience in general and would have great value in promoting the UNCOVER initiative

8. Maintain Australia's subscription to the IODP, and

- support robust and securely funded infrastructure and scientific agencies that will carry out sustained and consistent monitoring programs
- secure in-country specialist expertise by supporting climate scientists who will use the data generated from these programs

Researchers from Macquarie University examining mineral exposures in Yoqneam Road Tunnel, Israel.
CREDIT: VERED TOLEDO, SHEFA YAMIN

Air Force Research Laboratory's Cray XC30 supercomputer. Wright-Patterson Air Force Base, Ohio.
CREDIT: WRIGHT-PATTERSON AIR FORCE BASE / MIKEE HUBER / PUBLIC DOMAIN

6.2.2 Data

9. The Australian Government and state and territory governments should maintain and enhance support for Geoscience Australia and the state and territory geological surveys to create strategically targeted public-good geo-data sets having uniform national standards

10. Create, with uniform national standards, a high-resolution national-scale geochemical survey program of the uppermost 350 km. Integrate this program with high-resolution geophysical mapping to give an unprecedented but vital understanding of the layer of Earth on which our civilisation depends

11. Ensure the existence of high-quality geoscience data as baseline information to inform, track, and predict all impacts of resource development

12. Improve the openness and accessibility of geoscience data by:

- supporting Digital Earth Australia (previously the Australian Geoscience Data Cube)
- establishing and maintaining nationally consistent geoscience-focused research data repositories integrated with Digital Earth Australia
- ensuring that all data are FAIR-compliant
- establishing a national Laboratory Information Management System (LIMS) to ensure integrity of data from sample provenance to publication
- developing a secure platform for the permanent storage, and appropriate sharing, of confidential data on the resource endowment of Australia

13. Support for a National Drilling Initiative, and the creation of a national core repository with uniform national standards

6.2.3 Computational capability

14. Expand Australia's national computational capability. The requirement is to:

- be a world leader in computational applications for significant problems in complex systems
- further invest in computational infrastructure, including cloud-based platforms, to secure continued access to leading-edge machine processing and storage power
- retain and extend Australia's lead in geoscience simulation and modelling capability
- recognise and invest in the value of securely employed, trained technical staff to maximise the utility of advanced infrastructure for Australia's research scientists

6.3 Education

15. Government should invest in and support all levels of geoscience education. It should:

- recognise strategically important disciplines and specialisations as essential for the future of Australia, and support them accordingly, even though the economics of low enrolment numbers appear superficially unattractive. Universities must be given incentives to foster centres of educational and research excellence for the sake of strategic national needs
- encourage Earth Science graduates to obtain education qualifications and teach Earth Science. A range of mechanisms should be considered, potentially including fee waivers for courses (or joint degrees) that might not otherwise be financially viable

16. Professional societies, industry, government agencies, and universities should work together to provide integrated and multi-disciplinary education pathways for the next generation of geoscientists. In particular:

- disciplinary departments, research institutions, and industry must promote collegiality and collaboration both within and between themselves
- staff mobility between academia, industry, and government must improve
- geoscience should be embedded as a core subject within every level of Australian STEM education, and there should be explicit examples of Earth Science solutions to real-world problems in mathematics, physics, and chemistry textbooks
- government, academia, and industry should communicate the real-life applicability, relevance, and exciting opportunities that geoscience offers students, professionals, and Australians in general
- compulsory mathematics, statistics, and computer science units should be used to prepare graduates for increasingly computationally-intensive disciplines. Future geoscientists must be 'data literate' and ready for the big-data integration that will drive a step-change in geoscience
- geoscience graduates and practitioners should be given access to high-quality and nationally consistent ongoing professional development, closely aligned with the skills required to make geoscience truly predictive. Similarly, as the skills required to lead geoscience become more technologically advanced, established professionals must be given access to retraining and upskilling opportunities
- graduates must be able to better communicate the importance and relevance of geoscience to the broader public, for example by including science communication courses or workshops within geoscience degrees
- detailed strategies to expand access to geoscience courses in the tertiary sector must be developed, including attracting overseas students to study in Australia

17. Professional societies and the National Committee should continue to support the creation of geoscience teaching resources, consistent with the national curriculum, to enable improved and engaged teaching of geoscience in primary and secondary education. Geoscience must be highly visible in STEM curricula

6.4 Advocacy

18. The geoscience community must cultivate a pervasive appreciation and understanding of the importance and relevance of geoscience in the broader community and strengthen the status of the geoscientist as a trusted advisor

Public communication activities play an important role in shaping perceptions of Australian geoscience.
CREDIT: GEOSCIENCE AUSTRALIA

Meetings and conferences provide valuable professional education opportunities.
CREDIT: GEOSCIENCE AUSTRALIA

Reddish-brown linear sand dunes stand out from among the bright white salt mineral deposits left behind by evaporated floodwaters. Great Sandy Desert, Western Australia.

CREDIT: NASA / PUBLIC DOMAIN

This image from NASA Terra spacecraft shows Lake Mackay, the largest of hundreds of ephemeral lakes scattered throughout Western Australia and the Northern Territory, and the second largest lake in Australia.

CREDIT: NASA / PUBLIC DOMAIN

Exceptional exposure of the Pembroke Granulite, Fiordland New Zealand, allows for detailed study of melt-rock interaction in the deep (40km) roots of a magmatic arc.
CREDIT: NATHAN DACZKO

Abbreviations

AEOS	Australian Earth Observing System http://auscope.org.au/future-directions
BOM	Australian Bureau of Meteorology http://bom.gov.au
CERN	*Conseil Européen pour la Recherche Nucléaire* (European Council for Nuclear Research) https://home.cern/about
ESWA	Earth Science Western Australia http://earthsciencewa.com.au
FAIR	Findable, Accessible, Interoperable, and Re-usable see doi:10.1038/sdata.2016.18
GLONASS	*Globalnaya Navigazionnaya Sputnikovaya Sistema* (a Russian GNSS)
GNSS	Global Navigation Satellite System (a generic term)
GOCE	Gravity field and steady-state Ocean Circulation Explorer http://esa.int/Our_Activities/Observing_the_Earth/GOCE
GPS	Global Positioning System (an American GNSS)
GRaCE	Gravity Recovery and Climate Experiment https://nasa.gov/mission_pages/Grace/index.html
IMOS	Integrated Marine Observing System http://imos.org.au
InSAR	Interferometric Synthetic Aperture Radar
IODP	International Ocean Discovery Program
NCI	National Computational Infrastructure http://nci.org.au
NCRIS	National Collaborative Research Infrastructure Strategy
TERN	Terrestrial Ecosystem Research Network http://tern.org.au
VLBI	Very Long Baseline Interferometry

Banded iron formations in Kalmina Gorge, Karijini National Park, Western Australia.

CREDIT: BY GYPSY DENISE [CC BY-SA 4.0 (HTTPS://CREATIVECOMMONS.ORG/LICENSES/BY-SA/4.0)], FROM WIKIMEDIA COMMONS

The story told by our planet is extraordinary—from its birth as a hot, molten ball 4.56 billion years ago to its current state of an outer shell supporting jostling continents and convective oceans. This is the stage on which we pursue our lives, and which geoscience seeks to understand. Geoscientists are uniquely placed to interrogate Earth's geological records and engage the community in discussion concerning our use of the planet's finite resources. Geoscientists can enrich human experience, telling of the intrinsic beauty and wonder of Earth. They can convey the message that geoscience is a human endeavour with its own rigour and beauty, while relating the story of Earth's grandeur, dynamism, and fragility.

This is a particular responsibility for the National Committee for Earth Sciences and allied professional societies, but it is also a tale all geoscientists can tell.

Geoscientists must ensure the community understands the depth of our dependence on Earth as a life-support system, and appreciates how geoscience research can provide the knowledge to responsibly manage our interactions with the planet.

Awareness and understanding of geoscience across the community, including government, thought-leaders, and industry stakeholders can create a culture that promotes informed debate on complex controversial issues of environmental, cultural, social, and economic importance.

This decadal plan reinforces this perspective and seeks to both inform and open discussion of the way forward over the coming decade of transition.