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Companion report to

Our Planet, Australia's Future

A decade of transition in Geoscience

Background information and extended commentary underpinning the Decadal Plan for Australian Geoscience 2018 – 2027

Contents

Earth Science encompasses the study of Earth and its origin, including geology and all aspects of other major sciences (physics, chemistry, biology and mathematics) related to our planet in the solar system. Technological advances for identifying, understanding and developing our planet's resources, including minerals, energy and water, generate great opportunities and, in turn, responsibilities for us all.

Earth Science offers unique and profound benefits to Australian society. This report charts a transformative course for Earth Science, a course that will drive it to unlock enormous benefits for Australia and our planet.

Vision

A collaborative, interdisciplinary Earth Science community, developing the comprehensive understanding of our vast continent and planet needed to responsibly manage Australia's resources, drive future prosperity, enable a more sustainable renewables future, and enhance the quality of life of all Australians.

Mission

To forge a deeper understanding of our complex planet and develop a new, predictive framework for resource exploration success, the Earth Science community will:

- provide and develop scientific excellence in geoscience to be a driver of the Australian economy and quality of life
- develop and deploy advanced knowledge and technology to understand Earth processes and to reveal our planet's past, present and future; to maximise the utility of the continent to Australia's peoples; to better understand the where and why of Australian resources; and to place Australia at the forefront of geoscience globally.

Executive summary

The coming decade will be a critical period in human history. It will see continued human-induced pressures on our planet that call for new understandings of, and innovative approaches to, sustainability. Earth Science will be a key component of the solutions to these pressures by providing increased access to key resources, most of which are now either deeply buried or hidden beneath cover.

To discover and access these resources, which are the key to a sustainable future using renewable energy sources, Australia's Earth science community must develop and deploy vastly improved technological capabilities; it must embrace an integrated, whole-Earth perspective in both theory and practice, acknowledging that our planet is a truly complex system. Earth scientists must develop new technologies and pursue data-driven advances in key study areas and in modelling, to increase knowledge and solve the challenges to continued success in resource discovery and extraction.

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

This report outlines how Earth Science can provide the necessary knowledge base to meet the future needs of our society. It identifies the transitions required of Australian Earth Science research over the next decade and identifies actions to maintain the safety, security, wealth, and wellbeing of Australia.

The following areas represent challenges for Earth Science.

Food sustainability

Agricultural productivity in Australia is based on a detailed knowledge of the rocks and soils that underlie our food-generating land areas. The rocks and minerals provide nutrients and critical elements to the foods we eat, and many Earth resources are used for fertilisers and other products used in agriculture. Earth Science will contribute to maintaining and increasing Australia’s agricultural productivity by continuing to develop programs in collaboration with farmers and agricultural organisations that aim to maximise our productivity, using the latest, cutting-edge technologies.

Australia’s energy future

Safe, sustainable and reliable energy supply for Australian society is a major challenge with lasting implications for our future wellbeing. Resources required for sustainable energy production are also changing, for example with diminishing reliance on coal and increasing reliance on renewables and batteries for energy storage. These changes provide new opportunities for Australian prosperity, which must be economically and environmentally viable. New research on these resources will be underpinned by a robust scientific understanding of each resource, and how the resource can be used for the greatest sustainable benefit.

Australia’s mineral resources future

Mining and mining-related activities contribute 10% to Australia’s economy. Mineral resources provide the basis for many aspects of our society: iron for industry, copper for electrical systems, cobalt for electric vehicles, lithium and rare earth elements for computer and communications technologies, gold and diamonds for jewellery, and so on. As we transition into the future, many of these resources will be in short supply, both in Australia and overseas, providing a threat to Australia’s wellbeing.

Australia is richly endowed with mineral resources but finding new deposits of many resources is difficult because they are either deep within the crust or buried beneath a cover of younger sedimentary rocks and regolith. To achieve increasing success in the discovery of these hidden resources, the Earth Science community will 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 upwelling heat and components from the Deep Earth (the core and mantle). All of these components have changed over 4.56 billion years of Earth history; as the planet cooled, the atmosphere and hydrosphere changed, life evolved, and the tectonic plates interacted across the surface of Earth.

Earth Science in Australia will develop a greater understanding of these interactions and develop a comprehensive 4-dimensional (3D through time) model of Earth. Our aim is to keep access to critical resources through mineral exploration and mining and as a driving force of the Australian economy for decades to come.

Geohazard research

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

We need major transformations in how Earth Science is organised and practised to generate a bigger-picture, holistic, systems-approach perspective to answer these grand challenges. As a result, Earth Science must grow and change in the coming years.

Building Earth Science capabilities

To address Australia's evolving priorities, Earth scientists will need to strengthen collaborations and skills across a broad range of scientific and social disciplines. Australian Earth scientists can lead the way in applying technology-enabled solutions to complex problems.

Training the next generation of Earth scientists

Earth Science encompasses elements of geology, biology, chemistry, mathematics, physics, big-data and high-performance computational capability. To ensure a critical capacity of highly-skilled professionals competent to deal with complex systems, the interdisciplinary nature of Earth Science should be fostered at all levels of education. Earth Science education at high-school levels is critical to ensure a continuing feed of students into the discipline.

Engaging with our community

As the interface between our planet and society, there is an imperative for Earth scientists to undertake research and development that benefits Australia. The research underpinning our minerals industry, water resources, food production and almost all urban development issues should reflect the implications for, and needs of, society.

Earth Science must play a crucial role in preparing future generations and addressing the needs of Australian society. Our knowledge must progress beyond mere description and inference to comprehensive analysis and understanding, and explicit, confident prediction about the ongoing evolution of our planet and its response to the growing presence and activities of humans.

1. Introduction: Setting the scene

Humans depend on the natural resources we derive from Earth—rocks, minerals, groundwater, soils, energy, agricultural products, building materials and even the habitable ground on which we live.

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 build, 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 intimate and inherently complex.

Earth Science investigates the processes and systems that underlie our common connection and dependence on Earth, encompassing Geoscience and extending and integrating these with knowledge of the processes that define Earth's atmosphere, hydrosphere, cryosphere, biosphere, lithosphere and deeper domains. Earth Science enables us to understand our planet, our evolution and our relationship with Earth. It also recognises Earth's context as one of many complex planets within our solar system and beyond.

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 nurtured through understanding Earth's processes and how best to work in balance with them.

Australia occupies an entire continent: the flattest, driest, broadest and most populated interface with the Southern Ocean. We have warm currents down both the east and west coasts, and abundant mineral resources mostly covered in ancient regolith—the variable, weathered layer between fresh rock and fresh air. Australia's marine jurisdiction covers an area almost twice the size of the land mass and 4% of the global ocean[1].

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

The dynamism of our planet is rapidly changing. Understanding plate tectonics led to a paradigm shift that recognised the dynamic processes of Earth’s crust and its interior on timescales much longer than a human lifetime. Events such as earthquakes, subsidence, sea level rise and volcanic eruptions have immediate impacts on human lives. There is also a consensus that human activities have a significant impact on Earth's dynamic processes and even its geology—that 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.

This new perspective of dynamism also applies to our ‘old, weathered, stable’ continent and 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 quality of life will depend on how effectively we manage resources on our finite planet. Geoscience must become broader to encompass the dynamic interplay with our planet’s atmosphere, hydrosphere, cryosphere, biosphere, lithosphere and the deeper Earth (the mantle and core). Using data and computational capability, multidisciplinary Earth Science can develop to solve many of our continent’s and our planet’s most pressing challenges.

2. A decade of transition

The coming decade will see continued human-induced pressures on our planet, calling for innovative approaches to sustainability. Concurrently, technological and computing advances will provide new tools to explore previously hidden aspects of the planet and its processes.

Earth Science must embrace these changes to expand the scope and scale of questions the discipline can answer.

2.1. Our relationship with our planet

The next decade will see the global human population increase beyond 8.5 billion people, with the associated increased demand for resources. Anthropogenic changes to the planet’s climate systems will continue to affect the atmosphere as well as terrestrial and marine environments. Cascading effects are expected on agriculture, risks of natural hazards, urban development, water resources and human health.

The skills of the Earth Science community will be essential in providing the evidence-based decision-making needed to ensure the appropriate use of our finite resources for a sustainable future.

Our perspective of the planet is also changing. Just as plate tectonics allowed us to see Earth as a dynamic, changing place, we need now to broaden our perspective further to recognise the Anthropocene, in which humans are having a profound effect on the surface of Earth and its waters and atmosphere.

2.2. Technology and tools

The rapid disruption of some sectors by information and communications technologies has paralleled the pervasive adoption of digital systems and infrastructure in almost all facets of modern information access and communication. Earth Science has already shared in the benefits of the information revolution. For instance, cheaper processors of increasing capacity have allowed more complex and realistic models; greater access to satellite data; more data-intensive resources (geophysical and geochemical models); faster communication of results; and 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 as they are integrated and can no longer be viewed separately.

Earth Science is about to undergo even more transformative 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 will also be developed.

Ubiquitous millimetre-level 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 hardware advances: machine-learning techniques will extract tangible information from reams 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, as well as data management, discovery and delivery systems, in addition to our traditionally strong laboratory facilities.

2.3. Earth Science: a discipline at the interface of our planet and society

Earth Science integrates principles from physics, chemistry, biology and advanced mathematical modelling into a geological framework, the study of a highly complex natural system that developed over billions of years and extends more than 6,300 kilometres beneath Earth's surface. It investigates timescales from the age of Earth down to nuclear processes (femtoseconds), on atomic to planetary scales. It lies at the intersection of the human and the natural world, drawing on other areas of science and bringing them together to form an integrated understanding of the world around us and how its interconnected systems support our lives.

At the same time as drawing from other disciplines, Earth Science has driven developments in many other disciplines such as analytical chemistry, mass spectrometry, the application of lasers, high-pressure experimentation, microbial processes and medical imaging techniques. The natural world offers significant challenges that often require Earth scientists to lead chemistry, computational physics and other disciplines into new frontiers.

Earth Science will be central to Australia's future. Our use and management of Earth and cultural resources, our ability to manage environmental and geological risks and to develop a prosperous and sustainable economy will be crucial.

2.3.1. Earth resources

2.3.1.1. Food and water

Increasing urban size and density has brought Australia's food and water resources into sharp focus.

Our water resources are scarce, highly variable and subject to strong competing interests. Science can make the most of Australia's agricultural capacity through water efficiency and improvements to different types and quality of soil. Earth Science research, in multi-disciplinary collaboration, enables us to understand and manage these precious resources using a whole-of-geological-basin approach.

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[2].

[2] Australian Academy of Science, 2017, Decadal Plan for Agricultural Science in Australia

Many knowledge gaps remain: 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-located infrastructure by AuScope, the Terrestrial Ecosystem Research Network (TERN) and other national research infrastructure providers will allow unprecedented integrated monitoring of Earth.

2.3.1.2. Minerals and energy

The Australian minerals industry has a long history of innovation that has underpinned its success—and continues to do so. The industry's direct economic contribution in 2015 was 8% of GDP and almost 60% of exports. This figure does not include 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)—are a 'dynamic minerals innovation complex' that extends far beyond commodity extraction ('mining' in the broadest sense).

Australia's rich mineral and energy endowment and our success at finding resources near the surface is well established. However, we lack the capability in exploration Geoscience to find and access mineral resources in the approximately three-quarters of our continent under post-mineralisation cover. Except for iron ore, coal and petroleum, Australia's current extractable resource base will decline in the next decade. More fundamental research is required to support exploration for gold, copper, base metals, rare earth elements, lithium and other non-bulk minerals that will be crucial for high-technology devices developed in the coming decades.

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 the high-value minerals of the future. This is the important challenge that the UNCOVER AUSTRALIA initiative seeks to address.

Australia's shift towards renewable energy sources will involve greater demand for copper, cobalt, gold, tantalum, rare earth elements and other specialty metals.

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 that 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 vehicles 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 somewhere between 5 and 15 kg (typically around 10 kg) of cobalt. Cobalt currently costs about US$60,000 per tonne.

Bloomberg New Energy Finance (BNEF) estimates that within two decades, 16% of the world’s 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 6400 tonnes) we will not be able to move en masse to electric cars without an enormous increase in our ability to find and produce cobalt.

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

Earth Science research was critical in the discovery of the oil and gas resources that powered the development of our modern society and Australia is well placed to capitalise on the increasing demand for natural gas in the coming years.

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. In turn, Earth scientists should ensure the science of its Earth context is communicated accurately.

2.3.2. Cultural resources

2.3.2.1. Archaeological science of the dreamtime

Geoarchaeology, geochronology and palaeoenvironmental studies have all informed our understanding of the early and continuous settlement of our continent. Earth Science knowledge and technologies have crossed disciplinary boundaries to contribute to archaeology, early history and anthropological studies. Understanding our continent's cultural as well as geological past is essential for the continued growth and development of Australian society.

Australia is home to the oldest living culture on Earth, which can provide a rich source of historical information about, for example, Earth systems, ecology, geomorphology, and land management. The long history and close relationship of the first Australians with the land provides perspectives on change and adaptation that may not be possible from within contemporary, mainstream Australian culture. This relationship could inform better land management practices for the future. Burial sites uncovered at Lake Mungo in 1969 revealed the area was continuously occupied through periods of radical climate and environmental change. Since then geoarchaeologists have continued to push back the dates we have for both the timing of arrival and dispersal of the first Australians, as well as the intricacies of their trade, industry and agriculture.

2.3.3. Managing risk, responsibility and accountability

2.3.3.1. Geohazards forecasting and preparedness

Risk management relies on effective monitoring and forecasting of natural hazards, such as earthquake, tsunami and volcanic eruption.

Geohazards and extreme events such as landslides, earthquakes, fires and floods will have greater impacts as the global population increases and the built environment expands its footprint. Significant research that investigates both deep Earth and surficial processes is required for better forecasting of the risks and hazards related to Earth's geology and systems. By understanding the underlying mechanics of our planet's processes, we can enhance our capacity to forecast these events and mitigate their impacts.

It is vital we have permanent and rapidly deployable monitoring infrastructure, data collection and analysis systems to map the spread, and to mitigate the consequences of, damaging events. We have integrated geohazard science with cutting-edge communication warning technologies. These systems are also effective in addressing and mitigating the impacts of other hazards such as bushfires and floods.

2.3.3.2. *Resilience to changing climate and environmental processes*

Earth Science has provided an analysis of past climatic variation essential to understanding disruptions to current and future climate systems. Knowledge of Earth's dynamic atmosphere, hydrosphere and cryosphere underpins our understanding of climate change, as well as informing adaptation and mitigation strategies.

It is not just human societies that depend on the wellbeing 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.

2.3.4. Leading the global economy

Like all areas of scientific research, Earth Science drives innovation and productivity growth in many ways[3]. Earth Science's central role in finding, using and managing Earth's resources has a direct impact on the economy and broader society.

Research infrastructure also has a demonstrable impact on the national economy. The net benefit to Australia from investment in research infrastructure by AuScope alone is approximately $3.7 billion in 2015-16 terms[4]. This impact is spread across fundamental Earth Science, resource exploration, the natural and built environment and spatially sensitive industries.

2.3.4.1. *World-leading innovations*

Australian researchers have led the world in areas of Earth Science including mineral exploration and METS, geochemical analytics, liquefied natural gas exploration, computational geodetic networking for global positioning systems (GPS), and forecasting of geohazards.

Innovations include instrument design and geochemical analytical techniques and methods that have opened new doors for both fine-scale analysis and fast-throughput applications. Earth Science has also pushed the frontiers of data-driven computing with a spatial context.

2.3.4.2. *Emerging global economic opportunities*

Earth scientists must harness the tools of the information economy to master large-scale data collection, interpretation and management. Advances in Earth Science will provide the understanding required to turn what were previously considered obstacles into new economic opportunities.

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[3] AAS, 2016, Economic impacts of advanced physical, mathematical and biological sciences to the Australian economy
[4] AuScope Infrastructure Program - evaluation of impacts. A Lateral Economics report for AuScope Limited – August 2016. http://www.auscope.org.au/wp-content/uploads/2017/02/Lateral-Economics-report.pdf

Australia's experience with mineral extraction and processing can be applied to other areas of innovative resource use, such as recycling industrial waste products into new materials. Knowledge of Earth's processes will also provide information about the viability of other industries, such as bioenergy and responsible disposal of bio-wastes.

Together with vast uranium and fossil fuel reserves, our continent has tremendous potential for renewable energy resource development. Our ancient continent offers opportunities for geologically stable storage, including for nuclear waste and carbon.

Case Study: Strategic Research Infrastructure provides the platform for world-class Earth Science research

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

One of the significant successes of these programs has been the development of national 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 around 200 kilometres apart. The network can accurately pinpoint shifts in the Australian continent. Along 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 has improved VLBI measurement points from 3 to 103 and provides accurate data for applications in a host of industries.

Strategic infrastructure investment has revolutionised the type and quality of data available for Australian geodesy researchers and has transformed geodesy into an underpinning capability of Earth Science. It provides a significant and measurable return on investment in the spatially sensitive industries sector[5].

Over the next decade AuScope will invest in an Australian Earth Observing System (AEOS). The AEOS will support the development of the *Downward Looking Telescope* described in the Chief Scientist's 2016 National Research Infrastructure Roadmap[6] through the provision of new observational, remote sensing and monitoring infrastructure. Perhaps more critically, the AEOS will revolutionise the way Earth scientists interact with national datasets in much the same way that the investment in GNSS revolutionised Australian geodesy research over the past decade.

eResearch infrastructure will provide national 3D datasets that are linked from the point of sampling in the field to the eventual publication of data or research papers using International Geo Sample Number (IGSN) identifiers. It will embed the FAIR data principles[7] 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 the Integrated Marine Observing System (IMOS), the Terrestrial Ecosystem Research Network (TERN), the National Computational Infrastructure (NCI), the Pawsey Centre, Geoscience Australia, CSIRO and the Australian Bureau of Meteorology (BOM).

[5] http://www.auscope.org.au/wp-content/uploads/2017/02/Lateral-Economics-report.pdf
[6] https://docs.education.gov.au/node/43736
[7] FAIR: Findable, Accessible, Interoperable and Re-usable – see doi:10.1038/sdata.2016.18

3. Grand science challenges for the decade of transition

We must advance our knowledge of the planet to develop robust predictive capability in many areas of Earth Science. Priorities identified here outline what is required to fill the knowledge gaps that currently stand between us and our future prosperity in Australia.

3.1. Australia’s evolution: the deep interior and deep time

A thorough 4D (3D through time) geochemical and geophysical understanding of our continent is a prerequisite to predict the existence and location of likely mineral deposits, robustly forecast and prepare for geological hazard events, and to understand our continent in the context of Earth and 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 of Earth that forms and supports Australia. Building this knowledge of the physical and chemical systems of Earth will bring success in tackling the range of fundamental challenges outlined below.

Earth’s crust, continental and marine, is the source of the physical resources required for our civilisation: minerals and energy, water and soils, and habitable land. Our understanding of Earth today is strongly informed by what we know of our planet’s deep history, which is in turn derived from our understanding of the early solar system.

Fundamentally, heat energy drives the evolution of our planet: the temperature at the boundary of Earth's inner core is estimated to be about 6000°C. This heat energy deep within Earth dictates deep structure and shapes the processes that form oceans, continents, and the natural resources on which society relies. These energy processes also control many of the geological hazards on the planet’s surface, such as earthquakes, volcanoes and tsunamis. Investing in predictive and forecasting capabilities for such hazards will also help to identify valuable mineral and energy resources.

It is imperative that the Australian Earth Science community investigates the evolution of our own continent, including its territories, marine area and plate margins, spanning the surface to the core, almost 3000 km below. The aim is to reveal its deep structure and composition, to define and understand the variables that have contributed to its current state. Australia has a land area of approximately 7.7 million km^2, which is ~5% of the total land area (148 million km^2) of the planet. Considering that 70% of our planet is ocean and Australia is the sixth largest country by area, we have a unique opportunity, and responsibility, to map the Deep Earth beneath us.

We have an array of tools that can be further refined, along with new ones that must be developed, to deliver greater resolution and knowledge about Earth's structure and behaviour. The breakthroughs required in remotely-sensed geophysical methods will need vastly improved knowledge of the physics, composition, structure and temperature of rocks at depth to make the interior of our planet more knowable.

3.1.1. New geological, geophysical and geochemical capabilities: higher resolutions at larger and smaller scales

Over the past decade we have developed instruments, methodologies and techniques to image and determine the composition of crust and mantle materials at the atomic-, nano- and micro-scale. Combining these techniques with the now readily obtainable elemental and isotopic analysis of minerals allows a paradigm shift from the previous rock-dominated datasets to large-scale mineral datasets. These mineral-based datasets will reference the spatial context and physical characteristics of the minerals analysed and facilitate holistic interpretation.

Similar progress is required to advance our understanding of the role of deep fluids, including how energy and mass are transferred to the crust, and how geochemical domains form in the mantle. New experimental techniques will allow in situ observation of fluid–rock processes in new-generation experiments that can simulate deep-Earth conditions; for example, close control of fluid reactions and redox conditions at crustal pressures and improved multi-anvil and diamond-anvil experiments that reach pressures of the lower mantle and core with previously unattainable precision. The combination of such new knowledge with geophysical signals may be the key to identifying ancient and new fluid pathways in the crust and mantle at different scales.

The maturity of ambient noise methodology is revolutionising seismic tomography by removing the traditional reliance on data obtained from earthquake events. This is especially useful because the continent of Australia lies in a seismically quiet zone, so conventional seismological techniques may not offer robust coverage. The application of high-resolution ambient noise tomography to our continent will bring about a new perspective in our ability to image beneath Australia. It will enable us to determine our continent's structure at all scales from the surface to the convecting mantle, providing insights into the regolith, sedimentary basins, crust and lithosphere.

Future approaches and applications may include:

- inversion techniques using ambient noise with novel tomographic treatment of surface waves
- similar approaches with data collection at grid spacings that yield higher resolution and deeper results
- digital integration of datasets spanning seismic information, electromagnetics, gravity, geoid height, elevation, heat flow and other parameters
- data from appropriately spaced surface sensor arrays that will lead to a transition from traditional 2D to 3D and ultimately higher-resolution imaging of the lithosphere and beyond.

Integrating large datasets of geophysical and mineralogical characteristics will enable a realistic geological model of the deep Earth. For example, the origin of electromagnetic anomalies detected in the deep crust, lithosphere and mantle is unknown, but integrating new geochemical methods, new experimental approaches, and in situ measurements of electrical properties may help to solve this puzzle.

Geochemical analysis and imaging capabilities at the nano- and micro-scale will evolve with the emergence of high-resolution techniques capable of analysing increasingly small concentrations of elements. Synchrotron hardware will provide new levels of information about mineral structures, deformation mechanisms, element speciation and crystal chemical insights.

In the decade to 2018, AuScope has developed world-class geophysical, geospatial and geochemical observational and laboratory infrastructure as part of NCRIS. It has also developed national geoscientific datasets, underlying data management and delivery systems, simulation, modelling, analytics tools, discovery and delivery portals. The next decade will require expansion of these infrastructure platforms and close integration with aligned systems, advanced by research organisations such as Geoscience Australia, CSIRO and the state geological surveys.

3.1.2. Global and planetary science

Placing the Australian continent within the broader context of Earth and the other terrestrial (rocky) planets of Mercury, Venus and Mars will add to our understanding of both its formation and subsequent evolution. Earth's composition, and natural resources, are inherited from constituent building blocks which are sampled in the meteoritic population. In addition, Earth's evolution to its current state—atmospheric evolution, tectonics, biological development, and mineralisation potential—is but one possibility of how things could have worked out, and the divergent evolution between Earth and, for example, Venus, is not well understood.

New techniques using extinct radioisotopes (those no longer present naturally but evidenced by their decay products), together with geodynamic models, are shedding new light on Earth's earliest evolution. Applying the same techniques to materials from around the solar system tells us much more about the system in which Earth, and our continent, formed. New understanding of the composition, structure, and deep history of Earth—particularly our portion of its surface—goes together with advances in our fundamental understanding of planetary bodies.

Exploring other planets and remote, completely unknown environments also provides design inspiration for sensing, navigation and other systems. Designing and testing such systems on other planets has helped to advance technology on Earth. For example, the robust, deployable geological sensors on the Mars rovers are also suitable for autonomous deployment to remote or inhospitable environments on Earth and such interplanetary endeavours have pushed the boundaries of engineering and robotics capabilities.

Australian scientists must continue to lead in niche areas of the international terrestrial and space science research effort. Miniaturisation of space hardware is reducing the barrier to entry for researchers. Space-based and Earth observation technologies have had famously high-impact innovation spinoffs in the past, and this trend is only set to accelerate.

3.2. The real-time dynamism of Earth's crust

Some Earth processes occur on much shorter timescales than the maxim 'geological time' implies. Many processes are observable over periods ranging from years to milliseconds, and it is the rapid processes that present acute geohazards to humans.

Dramatic improvements in remote sensing and Earth observation techniques have advanced our understanding of the dynamic nature of Earth, providing capability to look at our planet and probe ongoing geological, terrestrial and anthropogenic processes in near real-time.

Many Earth processes exhibit geometric or physical-property signatures that can be measured with satellites. Global Navigation Satellite Systems such as the USA's GPS, Russia's GLONASS, China's BeiDou and the EU's Galileo can measure changes on the surface of Earth with sub-centimetre accuracy. Optical and radar imaging missions can map the land, ice and ocean surfaces to unprecedented resolution and accuracy.

Gravity observation satellites, such as GRACE and GOCE[8], provide information on the changes in the gravitational field across the globe. Subtle variations that are recorded can be used to monitor mass transport of fluids or sediment on, or beneath, Earth's surface. This enables us to analyse signals relating to many processes such as volcanism, ice mass changes, the water cycle, fluid extraction and underground mining.

Planned national drilling initiatives will provide unique opportunities to deploy monitoring infrastructure on and below the surface of our entire continent. This will allow Earth scientists to monitor changes in stress accumulation, earth movement, groundwater and human impact with a fidelity and scale not yet achieved anywhere else on Earth.

This information will contribute to and inform our capacity to forecast some types of earthquake activity with much greater accuracy. Seismologists have long tried to identify indicators of impending seismicity, and current earthquake forecasting and prediction can in some ways be likened to early attempts at weather forecasting. The weather system, like Earth, is inherently complex and non-linear in its behaviour; small events can lead to significant effects in other locations in the system. Dramatic increases in the sensitivity and density of observing systems, coupled to rapidly advancing computing power, have improved weather models and forecasting capability.

Similar technological breakthroughs in sensing and computation should one day predict dynamic Earth systems as accurately and routinely as weather forecasts. New remote observation techniques such as real-time satellite tracking of surface deformation related to deeper stress accumulation have become available, and high-performance computing with machine learning is beginning to de-convolve multiple huge observational datasets. Forecasting seismic events may yet become possible.

3.2.1. Neotectonics

Some Earth processes are dynamic on timescales within human life-times, and our interaction with the surface of the planet can change it. Understanding short-term crustal dynamics and deformation becomes critical in this context. The integration of geodetic, geophysical and seismological data, enhanced by satellite monitoring, will allow informed decision-making to manage events such as coastal erosion and to assess the impacts of interference with the shallow crustal environment on, for example, groundwater.

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[8] The satellite-based Gravity Recovery and Climate Experiment, and Gravity field and steady-state Ocean Circulation Explorer, respectively.

Current models constructed with fewer data resources will be refined and improved by a continual stream of data that will enable us to track changes in our crust, such as millimetre per year scale horizontal and vertical movements of our tectonic plates, as well as localised phenomena such as ground subsidence or uplift, in real-time. These data will inform a wide range of hazard monitoring and management challenges. For example, accurately tracking crustal movement is essential to assess the impact of sea-level changes. The identification and monitoring of fracture zones will inform other aspects of basin management such as groundwater movement and extraction, the impacts of hydraulic fracturing, or urbanisation. These are only a few of the dynamic processes that can be mapped and monitored using advanced satellite-based techniques.

3.2.2. Sedimentary basins

Approximately half of Australia is covered by sedimentary basins. These basins host energy and mineral resource systems and underlie fertile agricultural land, underpinning much of Australia's economic wealth. The nature and dynamics of complex basin systems influence our ability to use these vital resources sustainably.

New scientific knowledge is necessary to understand, map and quantify the many resources they host. This is necessary to identify the geological constraints of importance, 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 should help with environmental management.

Sedimentary basins are the repository of valuable resources, including geothermal energy and hydrocarbon energy. Australia has many potential oil- and gas-rich sedimentary basins, both onshore and offshore, that are underexplored and untested. We can reduce the technical risk associated with their exploration and production by establishing: geodynamic processes and basin evolution; stratigraphic and geographic distribution of source rocks and the types of fluid they will produce (oil, gas or condensate); better prediction of reservoir properties; and improved prediction prior to drilling through enhanced geophysical techniques.

The regolith and its relationship to the solid crust has implications for ensuring the security of a variety of resources, be they soils, water, minerals or energy. A comprehensive understanding of the regolith will include the microbes and other biological influences in the system, as these can have a significant impact on soil development, health and productivity.

3.2.3. Satellite capabilities

As described earlier, satellite capabilities currently have wide applications and many more will become apparent over the next decade. Recent satellite gravity missions (GRACE, GOCE) have demonstrated the capability of real-time monitoring of Australia's hydrological and hydrogeological systems on a continental scale.

Satellite magnetics provide critical information on subsurface geological terranes. Satellite radar interferometry (inSAR) provides critical information on strain accumulation in the crust, informing earthquake and landslide risk as well as subsurface reservoir monitoring. Our GNSS reference station network—itself supported by satellite technology—combines with inSAR to underpin the geospatial industry. Hyperspectral imagery allows detailed classification of mineralogy, soil type, salinity, and soil carbon content in near real-time. The exponential growth in the volume, resolution and sophistication of satellite data, together with expanding ground sensor networks, will completely revolutionise the way we monitor Australia.

Missions for monitoring the Australian continent, including inSAR, satellite gravity, magnetics, and hyperspectral observations, and the maintenance of our network of GNSS ground reference stations, are critical to capitalise on new applications, systems and capabilities that will develop. Space-based sensing will remain necessary for Australia's sparse population to steward roughly one eighth of Earth's surface in a cost-effective way.

3.3. Interpreting change throughout the geological record

The Australian continent is often characterised as old, flat and stable, yet this description fails to convey the significance of the changes it has undergone through deep time. Those changes have shaped our current landscapes, yet much remains unknown. The coming decade will deliver new insights into the ways in which organic and inorganic molecules from the biosphere are cycled at Earth's surface, the deeper parts of the biosphere below Earth's surface, and ultimately the transformations that take place as rocks are buried to depths of several kilometres in Earth's crust.

3.3.1. Lithosphere-biosphere interactions

Geobiology employs molecular biology, environmental biology, genomics and organic geochemistry of the geological record to investigate the evolutionary synergies of life and the inorganic Earth.

Microbes drive 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.

Current understandings of the global carbon cycle do not allow confident predictions about the effects of our actions. An integrated and holistic multidisciplinary approach is needed to put all the pieces together to develop a predictive understanding of how carbon is cycled through the planet’s ocean–atmosphere system, biosphere and lithosphere and beyond (to the deep mantle), and how these processes maintain a stable and habitable planet.

Linked to this is renewed interest in global fluctuations in marine and aquatic productivity over geological timeframes and the importance of biosphere–geosphere interactions. The past few decades of research indicate ocean chemistry has varied markedly throughout geological time, especially in respect to its redox structure. On longer timescales, these changes have been driven by the tectonic forces that determine the movement of continents and the shapes of the ocean basins (Wilson Cycles). Volcanism, continental uplift and erosion combined with orbital-driven climate changes (Milankovitch cycles) determine when and how nutrients are delivered to the oceans, controlling marine primary productivity and, from that, the ecological health of the oceans and the generation of energy resources. Such concepts are continually tested and refined through evidence provided from detailed studies of the geological record, investigations of modern marine and lacustrine sedimentary environments, and investigations of the more ephemeral records held in the continental ice sheets.

Apart from the role that microbes play in the degradation of hydrocarbons in shallow reservoirs and the formation of biogenic gas, our knowledge of microbial processes taking place in subsurface sediments is limited. Recognising this shortcoming in scientific knowledge, the International Ocean Discovery Program has recently mounted several expeditions to specifically study the nature of the deep subsurface biosphere and the processes that sustain it.

Microbial activity can play a role in mineral formation and the deposition or precipitation of many forms of economically important commodities. Microbial alteration signatures can be used as a mineral exploration tool. Waste and contamination management strategies can also potentially take advantage of microbial activity, and huge environmental and economic benefits could be realised with better understanding of how these microbial communities interact with and mediate their environment.

The most obvious interactions between the biosphere and lithosphere are evidenced in the impact of human activity on the planet. Significant alterations have occurred to hydrogeological regimes in the form of dams and groundwater exploitation, along with the development of civilisations and their associated atmospheric, terrestrial and marine pollution. Most critical have been the unintended effects of agriculture, fishing, shipping and other activities that are altering the ecological structures of our oceans and coastal waterways with detrimental or unpredictable consequences for a nation whose population is heavily concentrated near its coastline.

The ways in which the lithosphere and biosphere interact are exceedingly complex and our current understanding is in its infancy. Biogeoscience will enable the development of a predictive understanding of this aspect of Earth.

Over the next decade, continued research into the evolution of microbial communities and the microbial mediation processes over a range of scales and diverse range of environments using combinations of geochemical and genomics methodologies will inform our understanding of these processes and facilitate the development of a predictive capability.

3.3.2. Life on our planet and in the solar system

We must continue to investigate the origins and evolution of life on Earth, as it deepens our understanding of life today. Reconstructions of ancient life depend on knowledge discovered in rocks that were at Earth's surface billions of years ago. Geological and geochemical signs of life on early Earth are extensively distributed across the globe. Australia offers the ideal field site to probe these questions given the extraordinary evidence of early life found on our continent—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.

Knowledge must be gained from studying modern environments to interpret evidence collected from Earth's oldest rocks. By studying the development and evolution of organisms that inhabit Earth's extreme environments, such as deep-sea vents, Antarctica, or volcanoes, we can begin to answer the questions that remain about the limits of life. In doing so, we can gain a better understanding of life on Earth and how it developed, to inform our curiosity about life on other planets.

3.3.3. Paleoclimate interpretations

The impact of human activity is now imprinted on the geological record, as acknowledged by the proposal of the Anthropocene as the latest geological epoch. Earth scientists understand that the climate is a dynamic feedback system of oceans, atmosphere and land masses, which has always changed through time. Earth scientists have also documented evidence from the geological record that the current rate of change is unprecedented, and climate change is linked to greenhouse gas emissions, rising average global temperatures, ocean acidification, land clearing and species extinction.

The most significant contribution Earth scientists can make to climate change science over the next decade is in establishing the rate and trajectory of change, with an appreciation of both natural-variability driven and anthropogenic-driven climate change. This will enable us to develop the predictive capability of Earth and its processes to better equip us to deal with the ongoing impacts of climate change on our planet's inhabitants and resources.

Comparisons with changes preserved in the palaeoclimatic record are an essential requirement for this predictive capacity. We can refer back to times when carbon dioxide levels of the atmosphere were at a similar level to today (400 ppm) during the middle Pliocene (3.6 Ma), or when climates were warmer, such as the Paleocene-Eocene Thermal Maximum (55 Ma; or indeed any of the Paleocene-Eocene hyperthermals), to understand more about possible ice coverage and ocean circulation patterns, along with the biotic response to these conditions. Such examples provide a hint of the useful evidence buried in the geological record that is waiting to be discovered.

We must also continue to look at the climatic fluctuations of the Quaternary (the past 2.6 million years), from the Ice Ages (e.g. 20 ka) when sea level was as much as 130 m below present levels to the Last Interglacial (125 ka) when sea levels were higher than today. These records will enable us to understand the impacts of sea level fluctuations on the global hydrological balance and the response of species distributions.

In Australia we have the potential for even greater insight, as people have inhabited this land for around half of the last cycle and witnessed both the colder, harsher conditions and the more rapidly rising seas. There are Aboriginal oral histories that capture these changes, which can be supplemented by the occupation patterns preserved in the archaeological and geological records[9].

A thorough understanding of the chemical and biological changes preserved in the ice core, soft sediment, coral, speleothem and other biogenic carbonates and tree ring records allows robust corroboration of the climate models that are being used to model the trajectory and impact of a changing climate into the future.

This is particularly the case through the Holocene (the most recent 11.8 thousand years), when sea levels and mean annual temperatures were comparable to pre-industrial conditions. Through this period, we can better understand the influence of ocean–atmospheric interactions on climate, tracking changes in the El Niño Southern Oscillation, Indian Ocean Dipole and

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[9] For example, [9] Williamson et al, 2015. Technology and Australia's Future. Australian Council of Learned Academies. Melbourne.

Southern Annular Mode, which are the dominant climate influences in Australia. Equipped with this background knowledge, we can better quantify the influence of human activities above and beyond natural variability. From this, Earth scientists and others will develop our predictive capacity for modelling future change.

This capability must also be fed by continued research into understanding the dynamics of the Antarctic ice sheets, Antarctic sea ice and the role the Southern Ocean plays in influencing them. Australia has a responsibility to continue essential investigations of southern hemisphere climate dynamics.

Projections of future sea-level rise depend on a rigorous analysis of these factors. Future changes in sea level have implications for coastal dynamics and geomorphology, and the habitability of our coastlines where most Australians live.

Models that target time periods or where the environmental response to climate is not certain, can tease apart these discrepancies and strengthen future projections. This will be critical in urban, infrastructure and aid planning, and will support appropriate mitigation, rather than simply reacting to climate-related hazards.

The response of the hydrological cycle to broader climatic change is also critical. The interaction between surface and groundwater resources and their impact on soil health, underpins the future food security of the population. Desertification, declining water supplies and failure of food crops during drought have destabilised civilisations throughout the archaeological record and are implicated in on-going humanitarian crises in the Middle East and North Africa.

3.3.4. Geoarchaeology/cultural geology

Studies of past climates also contribute and link to archaeological investigations of the cultural history of our continent. Geochronological techniques are being refined to extend the radiocarbon envelope and develop new methods to date residues, rock art and occupation sites. This provides insight not just for the longevity but also the complexity of Indigenous settlement and society, and the climatic context.

By coupling the archaeological record with the palaeoenvironmental and palaeoclimate records, we can better understand the influence of the first Australians on the landscape through time. This includes changes to vegetation patterns through fire regimes and selective harvesting, modification of waterways and impact on faunal populations. Australia's Indigenous archaeological and cultural heritage is a rich and little-understood source of information about Earth systems, ecology, geomorphology and land management. The long history and close relationship of the first Australians with the land provides perspectives on change and adaptation that cannot be gained from within contemporary, mainstream Australian culture.

3.3.5. Our resource and energy future

Earth Science knowledge underpins all resource and energy futures—providing safe, sustainable and reliable mineral and energy supply for global societies into the future. New opportunities must be supported and informed by a robust scientific understanding of each resource, how it can best be used, and the various factors that may affect development. Manufacturing industries supplying hardware for sustainable energy generation will require new sources of minerals.

3.3.6. Mineral systems

Australia's past success in mineral exploration relied initially on skilled prospectors, who built Australia's wealth through discoveries of outcropping or alluvial minerals. The advent of national geophysical surveys heralded the rise of 'smart prospecting' which delivered considerable economic benefits and established Australia as a major mineral exporter on the global stage. Shallow mineral deposits provided most of our exploration success. Recent trends in mineral exploration investment are not so positive and Australia's share of the international mineral exploration investment has fallen consistently for the past 20 years.

Approximately 70% of our continent remains under-explored because the depth of cover defeats current exploration methodologies. With properly targeted new knowledge about our continent this presents a unique and exciting opportunity with enormous consequences.

The UNCOVER AUSTRALIA[10] initiative is designed to generate breakthroughs in Earth Science that will lift mineral exploration success in the covered parts of Australia back up to the same levels we previously enjoyed in the uncovered areas two to three decades ago. UNCOVER AUSTRALIA[11] - is a collaboration between industry, government and academia to identify and prioritise the science required to break the barrier that cover presents and re-establish Australia as a preferred greenfield exploration destination.

UNCOVER AUSTRALIA embodies the transitions described in this report—technology is increasing the scope of the questions that can be answered at the same time as we require a much more holistic understanding of our continent and its mineral systems. As such, it is well placed to become an exemplar initiative of the decade of transition and requires the continued support of the Earth Science community. In achieving its goals, UNCOVER AUSTRALIA also stands to revolutionise our understanding of the Australian continent and develop new technologies that will have positive implications far beyond the minerals sector.

[10] www.uncoveraustralia.org.au
[11] https://www.uncoveraustralia.org.au/

3.3.7. Coal, oil and gas

Traditional fossil fuels—coal, oil and gas—will remain part of the Australian energy mix for the foreseeable future by the infrastructure investment that has already been made on both supply and demand sides. As noted earlier, Australia's vast onshore and offshore sedimentary basins host numerous coal, oil and gas resources, many of which have not yet been characterised. In contrast to many minerals, exploration technology for coal, oil and gas is mature. Australia's undeveloped resource inventory is large, and further refinements to exploration technology specific to these resources is not a national priority.

Australia supplies approximately 60% of the world's metallurgical coal and 20% of its thermal coal[12]. Public support for, and investment in, renewable energy technologies is likely to continue to grow, but there remains no viable alternative to metallurgical coal—Australia's primary coal export and a necessary requirement for iron- and steel-making.

Australia is poised to become one of the world's largest producers of liquefied natural gas (LNG) from its onshore and offshore developments. Significant new resources are expected to emerge from international drilling programs such as those planned in Australia's offshore basins underlying the Great Australian Bight and the Lord Howe Rise, and in onshore basins underlying the Northern Territory.

3.3.8. Nuclear energy

Australia is already one of the world's major uranium producers. Earth Science knowledge will necessarily underpin any further safe development and management of additional industries over the whole cycle, from mining to waste storage and safe disposal.

Australia's uranium deposits have the potential to offer abundant energy that could provide base-load power in a low-carbon future. Exploration for new uranium resources requires a predictive capacity for mineral deposits under deep cover—the challenges pertaining to uranium are no different from those addressed by the UNCOVER AUSTRALIA initiative and the future strategies that will flow from it.

In the coming decade, a major class of new development in Australia may be a low-level radioactive waste storage facility. If this is the case, rigorous assessments of potential impacts must be informed by the best possible Earth Science. While the politics of nuclear energy is beyond the scope of the Decadal Plan for Australian Geoscience, it is the responsibility of the Earth Science community to provide sound technical and geological knowledge to inform relevant issues.

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[12] Minerals Council of Australia, 2017. http://www.minerals.org.au/resources/coal

3.3.9. Geothermal resources

Australia does not have significant conventional hydrothermal energy resources; yet it has immense potential—though not uniformly distributed or necessarily aligned with population centres—for many types of non-conventional geothermal resources.

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 are endowed with 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 is also endowed with deep, non-conventional 'hot dry rock' resources, generally in the Otway 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 we require much better knowledge of Australian sedimentary basins and the deep Earth.

Geothermal energy continues to be a potentially important contributor to our nation's energy mix and will benefit from initiatives such as UNCOVER AUSTRALIA, which seek to transform how we understand our continent and the opportunities it may provide.

3.3.10. Geoengineering

Advances in engineering continue to enable new technologies for developing Earth's resources. Recent examples include the rapid rollout of hydraulic fracturing for coal seam gas extraction in Queensland, and the CO2CRC demonstration facilities for carbon capture and storage in the Otway Basin, Victoria.

Regardless of what the next new technology happens to be, it is essential Earth scientists develop a predictive understanding of our continent to assess the impact of change and to help inform affected people: the social aspects of new resource development cannot be ignored. Earth Science underpins engineering on and in Earth—including farms, mines, wells, roads, railways, landfill, other waste storage, and cities.

4. Transforming Earth Science

The practice of Earth Science in Australia will have to change over the coming decade if we are to address the grand challenges successfully. The conceptual breakthroughs required in the next decade and beyond will necessitate expanding our field of view, embracing technology, developing new methodologies and investing heavily in the next generation of Earth scientists.

A strong culture of pervasive and targeted advocacy engaging the community, government, thought-leaders and industry stakeholders will create a social culture supporting Earth Science such that Australians are aware of its crucial role in Australia's future.

4.1. A bigger picture view: developing whole-Earth capabilities

New approaches will be required to answer the most important questions Australians will face in the next decade and beyond. Earth scientists will need to strengthen and entrench collaborations across the breadth of their discipline as well as into other disciplines previously viewed as only tangentially related. This expanded view is already developing: new data, technology and tools are allowing unprecedented connections to be made into new areas of science such as biogeoscience, space science and materials science, and this trend is set to expand dramatically in the coming decade. Australian Earth scientists have an opportunity—and an obligation—to drive the cooperative development and application of technology-enabled solutions to previously intractable problems that are relevant to Australia.

4.1.1. Strategies to support answering the big questions

We also need to develop strategies and new methodologies to harness the unprecedented amount and variety of data that will be created as new Earth monitoring and other data streams come online, and to get the most out of new technological capabilities as they become available.

We can no longer confine our research questions to smaller, more manageable chunks, then extrapolate our findings to the wider system. This does not work with a complex system and so we must tackle the questions of how Earth functions and responds to change in their entirety.

A more holistic, integrated approach is required, characterised by:

- *Considering research questions of much larger scope.* Past practice includes reducing real-world questions down to a subset of solvable challenges within a single discipline. Removing the complexity from a problem simply by narrowing the scope may obscure valid solutions for the big problems
- *Acquiring and using a variety of data, often involving large volumes.* We need new methods of acquiring information about Earth that tell us more than ever before, more quickly and cheaply, but we also seek deeper insights through new methods of using, storing, fusing and extracting more useful information from everything we measure.

We are in the early stages of deploying big-data strategies in Earth Science and currently the transformational potential of such methods faces several obstacles:

- *Data accessibility*: large amounts of data are being generated by publicly and privately funded research. A central repository and catalogue is needed to collect, compile and archive all Earth Science data in a consistent format and make it available for research. Even the relatively small amount (compared with that held by private companies) of publicly funded Australian research data is not easily accessible. An investment in data standards, ownership and warehousing will unlock greater value from existing research and observations. The Australian Geoscience Data Cube[13], a partnership between Geoscience Australia, CSIRO and the NCI, is a valuable first step towards the type of capability that will underpin the future of Australian Earth Science
- *Training:* Earth Science courses do not typically address numeracy, or competence in data management. Australia is not currently preparing its next generation of Earth scientists for the type of research and methodology development that will be required
- *New methods*: The development and roll-out of new measurement techniques for parameters or relationships which we are currently unable to constrain, including proof of calibration and interpretation, underpins the future capability of Earth Science (as for all science disciplines). Readily available datasets with which to ground-truth or calibrate new methods will increase public and private development (e.g. national in situ geochemistry).

4.1.2. Strengthen and embed a collaborative culture in Earth Science

The challenges facing Earth Science research require significant and concerted collaboration.

4.1.2.1. Inter- and multi-disciplinary collaborations

A collegiate and diverse Earth Science effort is needed in the coming decade; solving Australia's most important questions will require an integrated approach to research that must include mathematics and computational sciences and reach into the social sciences.

Research investors and funding agencies must recognise the value of inter- and multi-disciplinary work and encourage it with funding pathways, with funding bodies giving weight to priorities collectively determined by the Earth Science community.

[13] http://www.datacube.org.au/

Large-scale, inter-disciplinary collaborations will be needed to support infrastructure requirements, where the scale of the required instrumentation will demand multi-stakeholder funding for both implementation and maintenance.

4.1.2.2. International collaborations

Earth systems extend beyond national boundaries (albeit often influenced by geology), and collaborations in Earth Science must also extend beyond our own border.

Many questions regarding Australian geology can best be informed by studying analogues on other continents, and vice versa, generating global partnerships and collaborations. On an even larger scale, 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 underpin international scientific collaboration.

Australian Earth scientists need appropriate support to work internationally during their research, and 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, with secure employment and immigration status while in Australia and appropriate rights and controls to the data that is generated.

4.1.2.3. Cross-sector collaborations

The challenges of the future 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 drives both groups towards a common purpose. This will best be served by an independent body or bodies that sits between industry, government and academia to focus the strategic agenda. The UNCOVER AUSTRALIA initiative shows this approach is both possible and beneficial.

4.1.3. Technology-driven transitions

The next decade must also see development and refinement of the tools, infrastructure and practices needed to support research and create a well-resourced, effective and successful research environment. These tools must be deployed wisely and include human–computer interactions and judicious human review of outputs and interpretation.

Progress in computer processing power, algorithmic efficiency, data management and networking capacity has grown exponentially and transformed many aspects of our lives; reaching into 'everything society does and leaving in its wake a transformed economic, social and scientific landscape'[14].

Large datasets are already at the core of mineral exploration techniques, yet the information and communication sciences, engineering and related technologies are just beginning to achieve the scale and deployment-readiness required to successfully tackle complex Earth Science research. Examples include global convection simulations that can model the motion of plates and the deformation of continents, crustal-scale models that provide insight into the dynamic processes that formed the Australian continent and its minerals, and a 3D multi-observable probabilistic inversion of seismology data that produces thermal and compositional models of Earth's interior that can be interpreted geologically.

The 2016 National Research Infrastructure Roadmap identified, as a priority, the establishment of next generation Earth monitoring infrastructure and the development of 'downward looking telescopes'. It proposed 'enhancing capability in AuScope to include new Earth Monitoring data and tools' and to 'utilise new remotely sensed data and visualise findings'. A generational shift is required in technology resources and interconnectivity of all facilities, including establishing a virtual laboratory network to enable sharing large data (including digitised collections) and improved real-time communication.

The development of Earth Science capability will likely follow closely advances in information and communications science and technology. Australian Earth scientists have an opportunity to play an active role in the development of new computational methods, protocols and hardware tailored to problems in Earth Science, as well as develop supporting technologies.

Advances in information and communications technologies (ICT) are steadily broadening the scale of questions Earth Science can tackle. However, to successfully realise the opportunities, we will need to develop new technologies, methods, data analysis and fusion capability, and the capacity for further development. In short, we require a massive expansion of carefully targeted and collected data, analysed by skilled researchers.

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[14] Australian Academy of Science, 2013, Future Science Computer Science: Meeting the scale challenge.

The computational capacity of the Earth Science community is heavily supported by national infrastructure schemes, such as the National Computational Infrastructure facility (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 Earth Science into the big science realm.

Historically, Earth Science 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 could be supported through software support and development for developing, expanding, parallelising, and optimising available Earth Science software to make full use of these facilities; and low- and mid-tier level computing infrastructure from department-level servers up to university consortia, which facilitate testing, development, code optimisation, and student learning.

The latter is largely supported at a university level but needs strategic support from the broader Earth Science community. The former—software development—was supported by the previous NCRIS round under AuScope and led to the development of software such as Underworld[15], eScript[16], gPlates[17] and various inversion suites[18].

The final critical element of a national computational capability in Earth Science is personnel. The evolution of Earth Science into a big-data and simulation-intensive field requires the training and nurturing of a computationally literate cohort of undergraduate and postgraduate students who are also experts in Earth Science.

4.2. Investing in education and training

The transitions discussed in this report will require many highly skilled professionals to execute. At a time when Australia's educational performance in both basic literacy and STEM subjects is falling relative to international standards, a serious reinvestment in all levels of education will be required to maintain our competitiveness in the medium to long term.

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

[16] Gross, L., Bourgouin, L., Hale, A. J., & Mühlhaus, H. B, 2007, Interface modeling in incompressible media using level sets in Escript. *Physics of the Earth and Planetary Interiors*, *163*(1), 23-34.

[17] Williams, S., Müller R.D., Landgrebe, T. C.W., Whittaker, J.M., 2012, An open-source software environment for visualizing and refining plate tectonic reconstructions using high resolution geological and geophysical data sets, in: *GSA Today*, 22, no. 4/5, doi: 10.1130/GSATG139A.1.

[18] Sambridge, M., Bodin, T., Gallagher, K., & Tkalčić, H., 2013, Transdimensional inference in the geosciences. *Phil. Trans. R. Soc. A*, *371*(1984), 20110547.

Technological progress is also changing what is required of the education system. The skills and attributes that enable students to keep pace with change are set to become just as important as the deep domain knowledge that was once the sole focus of our education system[19].

4.2.1. Primary and secondary Earth Science education

In the schools' sector, Earth Science education should cover fundamental aspects in the general science syllabus from primary to junior high school levels and provide the option for as many students as possible to elect to take more advanced studies in senior high school.

Current challenges for Australia include:

- falling literacy and numeracy among Australia's school age cohort, which will have to be addressed as part of *any* plan for Australia's future prosperity
- lack of teachers with higher qualifications in Earth Science[20] coupled with a lack of incentives to entice Earth Science graduates to enter teaching
- resourcing and teacher mentoring, currently only provided in a limited form by organisations such as Earth Science Western Australia[21].

Units such as those provided by Primary Connections[22] or Science by Doing[23] that provide comprehensive resources for teachers as well as students will remain important.

4.2.1. Tertiary and post-graduate education: the university sector

In the tertiary sector it is important that Earth Science graduate and higher degrees be widely available and be designed to yield competent professional Earth scientists. Given the demonstrated fundamental importance of Earth Science to our society, university students pursuing other science or non-science degrees would also benefit from access to Earth Science options (courses, minors and even majors) within their programs.

Current challenges for the Australian tertiary sector include:

- responding strategically to the changing demands on the education system. Degree and higher-degree structure and content are already responding in an ad hoc way, but ongoing planning and adjustment is needed to balance domain knowledge with work-ready skills and future-ready attributes in students
- encouraging collaboration between teaching institutions to establish consistent pre-

[19] Williamson et al, 2015, Technology and Australia's Future. Australian Council of Learned Academies. Melbourne.
[20] 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 Earth Science and a number of other disciplines.
[21] http://www.earthsciencewa.com.au/
[22] https://primaryconnections.org.au/
[23] https://www.sciencebydoing.edu.au/

requisites for Earth Science courses, to ensure a supply of technology-capable Earth Science graduates; develop a common or consistent first year program, to facilitate student mobility into small or specialist university Earth Science departments around the country; and develop teaching collaborations between small or specialist university Earth Science departments in the same region to provide well-rounded Earth Science courses.

A further structural challenge for tertiary and post-graduate Earth Science education providers is the current demand-driven funding model is not clearly tied to national workforce needs. A recent performance review of the Australian innovation, science and research system[24] expressed concern at the current trend of falling numbers of STEM graduates. The current model places decisions about student numbers—hence university funding—in the hands of teenagers rather than long-term planners.

4.2.2. Post-educational and continuing professional training

Ongoing professional development will become increasingly important as the pace of progress increases. Many professional associations already require members to undertake a minimum number of professional development hours to retain membership or a specific status, yet the Earth scientists of the future will need to embrace life-long learning rather than occasional courses. Universities, professional associations, learned societies and employers will need to collaborate to identify areas for development and provide opportunities and resources for life-long learning.

4.3. Advocacy: engaging the community at all levels

There is a strong imperative for Earth scientists to ensure the community understands and appreciates the depth of society's dependence on Earth Science research.

Awareness and understanding of Earth Science across the community, including government, thought leaders and industry stakeholders, will create a culture that enables 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—with an outer shell of continents and oceans that we inhabit and on which we rely for our lives. Earth scientists are uniquely placed to interrogate Earth's records and engage the

[24] Innovation and Science Australia (2016) Performance Review of the Australian Innovation, Science and Research System 2016. Commonwealth of Australia. Canberra. www industry.gov.au/Innovation-and-Science-Australia

community regarding our society's use of Earth's finite resources. They are capable of enriching human experience of the intrinsic beauty and wonder of Earth by conveying not only Earth Science as a human endeavour with rigour and beauty, but also the grandeur, dynamism and fragility of our planet.

5. Abbreviations

AEOS	Australian Earth Observing System http://www.auscope.org.au/future-directions
BOM	Australian Bureau of Meteorology http://www.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://www.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://www.esa.int/Our_Activities/Observing_the_Earth/GOCE
GPS	Global Positioning System (an American GNSS)
GRaCE	Gravity Recovery and Climate Experiment https://www.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

SBMI	Sedimentary Basin Management Initiative https://www.carltonconnect.com.au/wp-content/uploads/2016/01/SBMI-Position-Analysis.pdf
TERN	Terrestrial Ecosystem Research Network http://www.tern.org.au
VLBI	Very-long-baseline interferometry

6. Glossary

Anthropocene	An informal term for the period during which human activity has been the dominant influence on climate and the environment; suggested starting dates range from a few hundred to a few thousand years.
Anthropogenic driven climate change	Worldwide change in surface, atmosphere and ocean temperature as well as perturbation of other parts of the climate system correlated to human-related emissions of greenhouse gases.
Biosphere	The part of Earth's environment in which living organisms are found, and with which they interact.
Cryosphere	The part of Earth where the surface is frozen, comprising the area covered by ice sheets and glaciers, permafrost regions, and sea areas covered by ice, at least in winter.
Deep Earth	The dynamics and the structure of Earth's interior, usually explored through seismological tools.
Diamond anvil	Experimental setup that uses either a lever arm, tightening screws or pneumatic / hydraulic pressure to compress a sample between two diamonds.
Ediacaran fauna	Late Precambrian animals (e.g. jellyfish, soft corals and worms) first found in Ediacara, Australia, dated to about 640 Ma. They come from a shallow, littoral, marine environment and appear to have been stranded on mudflats or in tidal pools.
Element speciation	The distribution of a defined chemical species of an element in a system.
Femtosecond	One quadrillionth, or one millionth of one billionth, of a second (10^{-15}s).

Geoarchaeology	Multi-disciplinary approach which uses the techniques and subject matter of geography, geology and other Earth sciences to examine topics which inform archaeological knowledge and thought.
Geochronological	Record of geological events following the order in which they occurred.
Geochronology	Determination of time intervals on a geologic scale, through either absolute or relative dating methods.
Geodesy	The science of measurement of the shape or figure of Earth and its gravitational field.
Geodetic	The shape that most closely matches mathematically the figure calculated by geodesy.
Geoid height	Height of the mean sea level relative to a given ellipsoid of reference.
Geomorphology	The scientific study of the land-forms on Earth’s surface and of the processes that have fashioned them.
Hydrosphere	The mass of water which exists on or close to Earth's surface.
Hyperspectral imagery	Imaging technique based on the analysis of the electromagnetic spectrum to find objects, define the type of material and reveal undergoing processes at a pixel scale.
Hyperthermals	Any of several brief geological periods of global warming.
Indian Ocean Dipole	Irregular oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean.
ka (in the context of Last Interglacial (125 ka))	Abbreviation meaning ‘thousand years ago’.

Lacustrine sedimentary environments	Combination of physical, chemical and biological processes associated with the deposition of a particular type of sediment in lakes.
Lithosphere	The upper layer of the solid Earth, comprising all crustal rocks and part of the uppermost mantle. It comprises numerous blocks, known as tectonic plates and its thickness is variable, ranging from 1 km to 300 km, depending on the geological setting (i.e. young oceanic lithosphere vs old continental lithosphere).
Ma (in the context of the middle Pliocene (3.6 Ma))	Abbreviation meaning 'million years ago'.
Paleocene-Eocene	Geological epoch that lasted from about 66 to 34 million years ago.
Palaeoclimate	Past climate inferred from the traces left behind in the geological record.
Palaeoenvironmental	Related to the combination of physical, chemical and biological processes that existed in the past and can be inferred from the traces left behind in the geological record.
Regolith	General term for the layer of unconsolidated (non-cemented) weathered material, including rock fragments, mineral grains and all other superficial deposits, that rest on unaltered, solid bedrock.
Satellite radar interferometry	Technique that uses the amplitude and phase of two radar images to obtain high-resolution topographical maps of a zone of interest.
Sedimentary basin	A subsiding area of Earth's crust with accumulations of sediment.
Southern Annular Mode	Also known as the Antarctic oscillation, a low-frequency pattern of climate oscillation in the southern hemisphere.
Speleothem	Secondary mineral deposits formed in caves, including stalactites, helictites (having spiral form), curtains, ribbons, and stalagmites.

Stratigraphic	The relative spatial and temporal sequence of rock strata.
Stromatolite	A laminated, mounded structure, built up over long periods of time by successive layers or mats of cyanobacteria and trapped sedimentary material. Stromatolites are found in shallow marine waters in warmer regions.
Tomography	Any technique by which the characteristics of a subsurface volume can be represented graphically in 2 or 3 dimensions.