Geology and mineral resources of the Northern Territory

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Chapter 1: Introduction

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The Northern Territory of Australia covers an area of about 1.35 million km² and comprises ninety 1:250 000-scale topographic mapsheets. First Edition geological mapping of these mapsheets was completed in the early 1970s by the Bureau of Mineral Resources (BMR), later renamed the Australian Geological Survey Organisation (AGSO) and now known as Geoscience Australia (GA). From 1970 to 1990, BMR and the Northern Territory Geological Survey (NTGS) jointly conducted Second Edition mapping of selected regions. Subsequently, NTGS took over the principal role of mapping throughout the Territory and Second Edition mapping of selected regions of the NT is ongoing. Many economically important regions have also been mapped at 1:100 000-scale.

For over a century since the pioneering work of early explorers such as HYL Brown (Figure 1.1), numerous government geologists have contributed towards the current understanding of the geology and mineral resources of the NT. Their observations are detailed in numerous geological maps, reports, explanatory notes, bulletins and records. Apart from these government data, there are a large number of publications and reports from academia and mineral and petroleum exploration companies, much of which is held by the Minerals and Energy Information Centre of the NT Department of Mines and Energy.

Since the 1970s, many new developments have taken place in the geological sciences. These include high-quality airborne magnetic and radiometric surveys, new more advanced geochronological techniques, precise and fast geochemical analytical methods and the development of digital technology, which now plays a pivotal role in the collation, processing, interpretation and delivery of geoscientific information and maps. However, despite the large number of Territory-wide maps and digital datasets that have been published since this time, the NT has lacked an overarching document that described the NT’s geology and resource potential. Although detailed reports are available on individual geological mapsheets and on some provinces, this volume represents the first synthesis of available information dealing with the geology and mineral resources of the entire NT into a single publication. The overall aim is to provide industry, government and academia with a detailed reference point to the complex geological provinces of the NT and its associated mineral resources and exploration potential.

LAYOUT OF VOLUME

The relationship between geological time, geological provinces and mineral and petroleum systems is of fundamental importance and has guided the layout of this publication. The volume is subdivided on the basis of geological provinces, which are organised in ascending order with reference to the geological timescale. Mineral deposits within each province are divided on the basis of commodity. The petroleum geology of all basins with hydrocarbon potential is also described.

Chapters 2 and 3 cover Territory-wide topics; they respectively describe the geological framework of the NT and summarise the major commodities. Chapter 4 looks at the oldest known rocks within the NT, which are basement inliers of Archaean age within the Pine Creek Orogen and Tanami Region. Chapters 5–21 describe the NT’s Palaeo- to Mesoproterozoic orogenic provinces and overlying basins. Chapters 22–38 describe the Neoproterozoic to Palaeozoic orogenic provinces and other provinces, including the Neoproterozoic–early Palaeozoic Centralian Superbasin, late early Cambrian Kalkarindji Province, and the orogenic Irindina Province of the Arunta Region. Palaeozoic basins that extend into the Mesozoic (Bonaparte and Pedirka basins) are also included in this group. Chapters 39–42 describe the NT’s Mesozoic and Cenozoic basins.

Each chapter has a date of currency, which records the time at which compilation of each chapter ceased and editing and formatting commenced. This date may vary by as much as two years between chapters. For this reason, there may be some inconsistency between the currency of information between chapters.

Figure 1.1. HYL Brown, first Government Geologist of South Australia, made several visits to the NT and produced the first geological map of the NT in 1898, as well as 14 publications. Image courtesy of State Library of South Australia.
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**HISTORY OF GEOLOGICAL INVESTIGATIONS IN THE NORTHERN TERRITORY**

**1865–1945: Early investigations**

The history of geological investigations in the Northern Territory goes back to 1865, when HF Litchfield, a member of BT Finiss’s surveying party found a few specks of gold at the Finiss River, southwest of Darwin. Gold was also found at Tumbling Waters to the south of Darwin Harbour in 1869 by members of Surveyor General Goyder’s party. In 1863, administration of the Northern Territory was transferred from NSW to South Australia and from 1889, South Australian Government geologists made several investigations of the geology and mineral endowment of the Northern Territory. In 1870, a hole dug for the construction of a telegraph pole at Yam Creek, north of Pine Creek, yielded alluvial gravel containing coarse gold and this led to major gold rush in the Pine Creek area. Prospecting and mining activities increased rapidly and by 1875, several mineral fields had been discovered, including tin at Bynoe and Mount Wells, copper at Daly River, and silver-lead-zinc at Mount Evelyn and McArthur River. In the Arunta Region, several significant discoveries were made at about this time, including mica at Harts Range in the 1880s (Joklik 1955), alluvial gold at Arltunga in 1887, and reef gold in the same area shortly thereafter (Hossfeld 1937). Gold was discovered in the Tanami Region in 1900 (Davidson 1905).

Tate (1882) provided the first report dealing with the geology of the NT. Other mapping and geological investigations during this early period included those of Tennyson Woods (1864, 1886, 1889), Etheridge (1902, 1904), and Playford (1900, 1904). Between 1889 and 1911, HYL Brown (Figure 1.1), South Australian Chief Government Geologist, made numerous visits to the Territory and produced 14 reports covering the geology of its many mineral provinces. He also produced a series of reconnaissance geological maps of the Northern Territory through the 1890s and early 1900s, including the first geological map of the Northern Territory (Brown and Winnecke 1898, Figure 1.2), and a revised version published a decade later (Brown 1908, Figure 1.3).

In 1911, the Commonwealth Government took over administration of the Northern Territory from South Australia and appointed HI Jensen as the Chief Government Geologist, a position he held until 1916. Geological investigations were conducted on many of the mineral fields of the NT after his appointment. From 1926–1928, the Government Geologist, HA Ellis, examined many mineral occurrences and produced a number of significant reports and maps.

Although gold was recorded by HYL Brown from Tennant Creek in 1895, it was not until 1933 that a gold rush commenced in this area. In the first four years, this field produced a million dollars worth of gold. In 1934, WG Woolnough, Commonwealth Geological Advisor, carried out an extensive examination of the Tennant Creek goldfield and made a number of recommendations for its development, based on geological investigations at that time (Crohn 1976).

In 1935, the Aerial, Geological and Geophysical Survey of Northern Australia (AGGSNA) was jointly sponsored by the Commonwealth, Queensland and WA governments. From 1935–1941, AGGSNA carried out geological and geophysical surveys over most of the known mineral-bearing areas of the NT including the Brocks Creek, Maranboy, Pine Creek and Daly River mineral fields. A number of important reports and maps were completed at this time. The first detailed geological map of the Northern Territory (Hossfeld 1953) was essentially based on AGGSNA mapping activities during this period.

See Jones (1987) for a detailed account of the history of geological investigations and mineral exploration activities in the NT prior to 1946.

**1946–1978: BMR era**

In 1946, the Commonwealth Government established the Bureau of Mineral Resources (BMR). The discovery of uranium at Rum Jungle in 1949 provided much needed...
impetus for geological investigations by BMR in this area and from 1950–1953, several separate investigations were conducted on the uranium occurrences. At about the same time, PS Hossfeld compiled a preliminary geological map of the entire Northern Territory (Figure 1.4) and discussed the stratigraphic relationships, lithology and structure (Hossfeld 1953). In 1952, BMR set up a regional office in Darwin and employed a number of geological staff whose main aim was to carry out regional geological mapping. Systematic regional mapping of all of the NT commenced in 1953, resulting in the publication of First Edition 1:250 000-scale geological maps and explanatory notes through the 1960s and early 1970s. At the same time, the Resident Geological Section of the Northern Territory Administration (NTA) conducted geological investigations of local relevance. Until 1956, this section was run by geologists on secondment from BMR. However, from 1956 onwards, the NTA employed its own geological staff and opened offices in Tennant Creek and Alice Springs. In 1956, the number of geological staff was increased to eight and Norman James Mackay was appointed Senior Resident Geologist. The work in those years included the supervision of geologists in Darwin and Alice Springs, the inspection of prospects, some involving drilling programs, and the location of water bores for various station properties. In 1960, Peter W Crohn (Figure 1.5) was appointed as the BMR Senior Resident Geologist after his return from an Antarctic mission and he was involved in the discovery of the Groote Eylandt manganese deposits. In 1965, Crohn was succeeded by Dick Dodson who led the Darwin Uranium Group and the field party of geochemists and drillers that found the Woodcutters lead-zinc deposit in 1967, while looking for the extensions of Rum Jungle-style uranium deposits (Wilkinson 1996).

In 1970, the Northern Territory Geological Survey (NTGS) was created as a part of the Mines Branch of the NTA and ten geological positions were transferred from BMR to NTGS. Peter Crohn returned to Darwin to head the newly created geological section and Dick Dodson went back to Canberra. During his time Crohn expanded the project scope to include studies of minerals, groundwater, engineering geology, construction materials, geochemistry and geophysics. In 1976, he was appointed Director of Mines, a position he held until 1979. BMR continued to carry out regional investigations, whereas NTGS’s main functions involved mineral deposit and groundwater investigations. The first comprehensive

Figure 1.3. Northern sheet of revised Geological map of the Northern Territory of South Australia (Brown 1908, image courtesy of University of Queensland Library). Large stretches of NT coastline had been mapped since previous 1898 edition (Figure 1.1). Manganese outcrops, noted on Groote Eylandt by HYL Brown during this survey, were the subject of follow-up investigations half a century later by PR Dunn and PW Crohn, leading to the discovery of a world-class manganese deposit in this area.
map of the NT (Figure 1.6) awaited the culmination of First Edition 1:250,000-scale mapping and was compiled by D’Addario et al (1976).

During this period, a number of major world-class mineral discoveries were made (see Commodity Reviews), including uranium at Rum Jungle (1949) and in the East Alligator River Region (1969); zinc-lead-silver at McArthur River; manganese at Groote Eylandt (1960); bauxite at Gove (1949); and gold at Tennant Creek. Oil and gas accumulations were discovered in the Amadeus Basin in the mid-1960s.


In 1978, after the NT was granted Self-Government, NTGS became part of the NT Department of Mines and Energy. In 1979, Paul Le Messurier was appointed as the Director of NTGS (Figure 1.7). Under Le Messurier’s leadership, NTGS was reorganised into Regional Mapping, Metalliferous, Geophysics, Engineering Geology, Petroleum Geology, Environmental and Geoscience Information sections. NTGS functions changed from local mine site, groundwater and engineering investigations to regional geological mapping, geophysical surveys, environmental and metallogenic studies. The Environmental section was involved in the mapping of National Parks and the monitoring of mine sites. A branch office was established in Alice Springs and RBM Thompson was appointed as the first Assistant Director, Southern Region. AJ Hosking was appointed as Assistant Director, Northern Region in 1982 and was followed by CA Mulder in 1987, when Hosking departed NTGS. To meet NTGS’s new responsibilities, staff were increased to a total of 38 professional, technical and administrative personnel. In the first few years, BMR and NTGS geologists carried out joint investigations in the Pine Creek Orogen and Arunta Region. Subsequently, NTGS took over the sole responsibility of mapping, commencing in the Litchfield Domain of the Pine Creek Orogen. In 1982, NTGS had a staff of 25 geologists and 24 supporting cartographic and field staff.

In 1978, the Australian Science and Technology Council (ASTEC) carried out a review of BMR that was focused on defining its future role. One of the major recommendations of this review was that BMR should relinquish responsibility for the completion and revision of the 1:250,000-scale map series throughout Australia. However, it was considered that until the NT developed its own capability, BMR would continue to be

Figure 1.4. Preliminary geological map of the entire Northern Territory compiled by Hossfeld in the early 1950s. Note that because of extensive deformation, high-grade metamorphism and a paucity of geochronological information, the Arunta Region, and Musgrave and Irindina provinces are placed in the Archaean (‘Archaeozoic’). Image courtesy of National Library of Australia.

Figure 1.5. PW (Peter) Crohn, Senior Resident Geologist NT (1960–1965), Chief Government Geologist NT (1969–1978). Peter led the geological investigation at Groote Eylandt manganese deposits through its early definition stage. He expanded the functions of the NTGS from minesite studies to minerals, groundwater, engineering geology, construction materials, geochemistry and geophysics.
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responsible for mapping at this scale, in cooperation with the NT Government. These recommendations were a turning point in the history of NTGS and by 1981, it had assumed a greatly increased responsibility for geological mapping in the NT, as BMR gradually withdrew from such activities. The number of 1:100 000-scale mapping projects in which NTGS was participating increased from eight in 1979–1980 to eighteen in 1980–1981. The first NTGS-funded airborne geophysical surveys were flown over the Litchfield North, Barrow Creek, Huckitta and Kulgera areas in 1981 and involved a total of twenty 1:100 000 mapsheets. This led to the commencing of a long-term commitment to airborne geophysical programs that resulted in an average of one 1:250 000 mapsheet being flown every year from 1981 to 1999. In August 1983, NTGS published its first 1:100 000-scale geological map and explanatory notes (DARWIN1; Pietsch

1 Names of 1:250 000 and 1:100 000 mapsheets are in large and small capital letters respectively, eg BARROW CREEK, DARWIN.

Figure 1.6. The first comprehensive geological map of the NT awaited completion of First Edition 1:250 000-scale mapping and was compiled by D’Addario et al (1976). Scanned image courtesy of National Library of Australia.
1:6

1983), and by 1985, NTGS was conducting geological investigations across large areas of the Northern Territory, including the McArthur Basin, Tennant and Arunta regions and Musgrave Province. In 1987, a special initiative of $1 million was provided by the Territory Government to accelerate geological programs; this led to the publication of mineral commodity and petroleum basins studies as well as a mineral occurrence map of the Northern Territory.

In 1995, CA Mulder (Figure 1.8) was appointed as the Director of NTGS, a position he held until his retirement in 1998. During the 1990s, NTGS undertook major regional mapping campaigns, particularly in the McArthur Basin, Musgrave Province and Tennant Region.

During this period, a number of major mineral discoveries were made and important new mines opened in the Pine Creek Orogen, McArthur Basin and Tanami regions (see Commodity Reviews). Significant new mines included the Enterprise and a number of other gold mines in the PCO; several mines in the Granites and Dead Bullock Soak goldfields and the world-class Callie gold mine in the Tanami Region; the Woodcutters base metals mine in the PCO; the world-class McArthur River base metals mine in the McArthur Basin; and the Nabarlek and world-class Ranger uranium mines in the PCO. Significant oil and gas accumulations were also discovered in the offshore Bonaparte Basin.

1998–present: Modern exploration initiatives

In June 1997, Ross Fardon and Associates Pty Ltd completed a review of NTGS and recommended several changes, including in-house printing of maps and reports, the targeting of geological problems rather than map sheet areas, and an improvement in information technology and data handling capacity (Fardon 1997). In November 1998, the Minister of Mines and Energy announced that the Northern Territory Government would provide $16 million in additional funding to NTGS over a period of four years under the NT Exploration Initiative (NTEI). Dr RD (Dennis) Gee (Figure 1.9) joined NTGS as Director in October 1998 to lead the exploration initiative and to re-focus the geological survey in line with the recommendations of the ACIL Tasman review. The appointment of Dennis Gee, combined with additional funding through the NTEI, provided the catalyst for a change in direction for NTGS, resulting in exploration-focused, state-of-the-art geoscientific programs and a greater emphasis on enhancing the mineral potential of the NT, the collection and interpretation of geophysical data, and the development of a range of digital databases. A highlight of the NTEI was the coverage of vast areas of the NT, particularly in the south, with 400 m line-spaced airborne magnetics and radiometrics. Mapping activity was focused on the Tanami Region, Arunta Region and Victoria, McArthur, South Nicholson, Georgina and Birrindudu basins.

The NTEI was followed by the four-year (2003–2007), $15.2 million exploration initiative Building the Territory’s Resource Base, led by RG Brescianini (Director from 2002–2006, Figure 1.10), which included $13 million for new geoscience programs. Following a review of the success of these two initiatives (ACIL Tasman 2007), the Government announced a new Bringing Forward Discovery initiative, initially for four years, then extended to seven
years (2007–2014), with total funding of $25.8 million. *Bringing Forward Discovery* included a focus on improving the gravity coverage of the NT, as well as a program of collaborative industry grants for drilling and geophysics in areas with a paucity of geological knowledge (*Geophysical and Drilling Collaborations* program). Dr IR Scrimgeour (*Figure 1.11*) was appointed Director in late 2006 and has led *Bringing Forward Discovery* since its inception. Throughout the period from 2003–2011, NTGS was particularly focused on regional studies in the Arunta Region, Pine Creek Orogen and Georgina Basin, and on developing systems for improving the internet accessibility of data and information. Throughout the initiatives, specialist expertise has been brought in to NTGS programs through collaboration, particularly with Geoscience Australia and CSIRO.

Reflecting an increased emphasis on providing data of direct relevance to exploration, Dennis Gee initiated the Annual Geoscience Exploration Seminar (AGES) in 2000, to enable the annual reporting of NTGS results to the exploration industry. The abstracts volumes from these annual forums provide a detailed record of the progress of NTGS programs since 2000.

Between 1978 and 2012, NTGS published fifty 1:250 000 maps and thirty-one 1:100 000-scale geoscience maps, along with hundreds of associated published reports, records and external publications. Revised Second Edition 250 000-scale geological maps are now available for a large part of the Territory (*Figure 1.12*), and the NT has nearly complete coverage of 1:250 000-scale fully attributed geological map GIS tiles. Succeeding supervisors of regional mapping programs since the inception of NTGS have been DL Dundas, G DeRoss, BA Pietsch, IR Scrimgeour and...
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DF Close. M Ahmad supervised the Metalliferous section from 1981 and became Chief Geoscientist in 2005. CA Mulder supervised the Environmental section from 1982 to 1987. The Geophysical section has had B Simmons, TLF Findhammer and RG Brescianini as supervisors, and the Petroleum Geology section has been headed by P Sinicia, D Pegum and G Ambrose. Since 2000, significant advances have been made in the field of information technology and provision of geological maps and data to industry in digital formats. To lead these changes, Tracey Rogers was appointed in 2000 to head the Geoscience Information section of NTGS (now the Geoscience Knowledge Management program). Following a review of NTGS in 2004, the traditional subdivision into Regional Mapping, Metalliferous, Petroleum and Geophysics sections were combined into the Regional Prospectivity group, which undertakes all new geoscience programs in NTGS.

Since 2000, a large number of Territory-wide maps and digital datasets have been produced. There are NT-wide digital datasets have been produced. There are NT-wide digital datasets have been produced. There are NT-wide digital datasets have been produced. There are NT-wide digital datasets have been produced. There are NT-wide digital datasets have been produced.

Figure 1.12 Coverage of 1:250 000-scale geological mapping of the Northern Territory, as of February 2013.

Figure 1.13 Seamless airborne magnetic map of the Northern Territory.

2 Advanced Spaceborne Thermal Emission and Reflection Radiometer.
such as rare earths, phosphate, iron ore, mineral sands and vanadium, along with a major uranium exploration boom from 2007–2010. There has also been an increased focus on greenfields and undercover exploration, particularly in previously under-explored provinces such as the Arunta Region. Important discoveries over this period include the Barrow Creek-1 phosphate deposit in the Georgina Basin, the Mount Peake vanadium magnetite deposit in the Aileron Province, Myrtle zinc deposit in the McArthur Basin and a number of rare earth element discoveries, including Nolans Bore, Stromberg and Charley Creek. A number of mines commenced operations, including several heavy mineral sands mines in the Tiwi Islands, the Bootu Creek manganese mine, and a number of new...
and re-opened gold mines in the Pine Creek Orogen and Tanami regions. Onshore petroleum activity has also dramatically increased since 2010, with recognition of the potential of many of the Territory’s basins for large resources of unconventional petroleum, especially shale gas.

**ECONOMIC OVERVIEW**

The Northern Territory hosts a number of world-class mineral deposits, including manganese at Groote Eylandt, bauxite at Gove, phosphate at Wonarah, uranium in the Alligator Rivers region, base metals at McArthur River, and gold in the Tanami, Tennant Creek and Pine Creek areas.

The location of operating mines and major developing projects in November 2012 is shown in Figure 1.15. The total value of the available resources at these major deposits is in the order of $150–200 billion with past production of about $70 billion at current prices. In the financial year 2010/11, the NT produced mineral commodities valued at $3.44 billion. These data highlight both the importance of mineral industry to the Northern Territory economy and the prospectivity of the NT.

However, despite its long mining history and the presence of some 3000 known mineral occurrences, the Northern Territory is comparatively under-explored and has a substantial potential for major mineral discoveries of gold, copper, uranium, lead-zinc, platinum group metals, rare earth elements, nickel, manganese, bauxite, phosphate, potash, diamonds, tin, mineral sands, vanadium, tungsten, coal and several other commodities. Many of the NT’s sedimentary basins, both onshore and offshore, are also very prospective for conventional and unconventional petroleum.

The Palaeo- to Mesoproterozoic orogenic provinces of the Northern Territory have remarkable mineral potential for a variety of commodities and contain almost 80% of the known mineral occurrences. The most mineralised province is the *Pine Creek Orogen*, from which 16 different metals have historically been mined. Large uranium deposits are located in the vicinity of Archaean granitic complexes, close to the unconformity with overlying Palaeoproterozoic rocks in the Alligator Rivers and Rum Jungle uranium fields. Vein-type hydrothermal deposits of Au, Sn, Ag-Pb, W, Cu, Bi are clustered in the central part of the Pine Creek Orogen. Gold is the major commodity within this group of metals, followed by tin. Stratiform and stratiform polymetallic deposits are associated with carbonaceous sediments in the Pine Creek Orogen, such as the Pb-Zn-Cu-Ni-Co deposits in the Rum Jungle area. In the *Warramunga Province*, mineralisation is dominated by Cu-Au-Bi deposits, typically associated with magnetite-chlorite bodies. Mineralisation in late Palaeoproterozoic rocks in the *Davenport Province* is largely of hydrothermal origin and includes quartz-wolfram lodes and gold-bearing quartz reefs. The NT’s most economically important gold province is the *Tanami Region*. This area contains the world-class Callie deposit and has produced an estimated 8 Moz of gold over the last two decades. Gold, base metals, rare earth elements, ferroalloys and gemstone occurrences are widespread in the *Arranta Region*, and include a world-class rare earths deposit at Nolans Bore, and significant vanadium-magnetite, tungsten-molybdenum and copper deposits. The *Murphy Province* has significant potential for uranium and base metals deposits and hosts a number of known prospects. The *Arnhem* and *Warumpi* provinces and the NT portion of the *Musgrave Province* have received little attention from explorers and are arguably the most under-explored Proterozoic terranes on the Australian continent.

Overlying late Palaeoproterozoic to Mesoproterozoic basinal strata are also highly prospective. *McArthur Basin* sediments host the giant HYC (McArthur River) Pb-Zn-Ag and several other smaller base metals deposits, including enigmatic copper-bearing breccia pipes at Redbank. The basin is a continuation of the world-famous Carpentaria Zinc Belt, which contains substantial shale-hosted stratiform zinc-lead-silver deposits at Mount Isa, Hilton and Century in Queensland, and at McArthur River and Myrtle in the Northern Territory. Uranium and gold deposits are present in the southeast...
of the McArthur Basin and black shale intervals within the basin are very prospective for unconventional petroleum. The southern McArthur Basin also contains diamond-bearing kimberlites at the Merlin deposit. The Roper Group, in the upper part of the McArthur Basin succession, hosts iron ore deposits in the Roper River area, and has significant potential for shale gas and oil in the Beetaloo Sub-basin. The Tomkinson Province and Birrindudu Basin successions are time equivalents of the McArthur Basin, but are relatively poorly explored. Both basins contain minor base metal occurrences, and minor oil shows have been reported from the Birrindudu Basin. The Tomkinson Province also contains significant hydrothermal manganese mineralisation at Bootu Creek.

The NT’s Neoproterozoic to Palaeozoic basins contain nearly 400 mineral occurrences, mainly of base metals, phosphate and uranium, and many of these basins are also very prospective for petroleum. Significant deposits of uranium are hosted by sedimentary rocks of the Amadeus and Ngalia basins. The Amadeus Basin also has considerable potential for conventional and unconventional petroleum, and has producing oil and gas fields at Palm Valley, Mereenie and Surprise. The Georgina Basin is a premier target for phosphate exploration and hosts the world-class Wonarah and a number of other significant deposits. The offshore Bonaparte Basin is a world-class petroleum province that contains a number of producing oil and gas fields, and the onshore basin hosts significant Mississippi Valley-style zinc-lead-silver deposits. Neoproterozoic to Palaeozoic basins that are also prospective for petroleum include the offshore Arafura Basin and the stacked Warburton and Pedirka basins in the southeast of the NT. The Pedirka Basin also contains substantial resources of coal at depth.

The Mesozoic Carpentaria Basin has outstanding potential for manganese. It hosts the giant Groote Eylandt manganese deposits and several under-explored manganese occurrences. The onshore part of the Money Shoal Basin provides much of the construction material (sand, aggregate, dimension stone) for the Darwin region and offshore areas of this basin are very prospective for petroleum. The Eromanga Basin, in the southeastern NT, also has considerable petroleum potential.

The Cenozoic coastline of the Northern Territory contains a number of bauxite profiles and hosts the world-class bauxite deposit at Gove. It also hosts the heavy mineral sands deposits of the Tiwi islands. Inland, in the central and southern parts of the Northern Territory, a number of calcrete- and palaeochannel-style uranium occurrences have been reported.

GEOCHRONOLOGY

One of the most important tools for understanding the geology of the NT is radiometric dating. A large proportion of the NT’s rocks are barren of fossils and are therefore very difficult to date by any other means. The distribution of NTGS and NTGS-GA geochronology sites in the NT is given in Figure 1.16.

The earliest radiometric age determinations on Northern Territory rocks were made in 1960, when granite and other rock types from the Pine Creek Orogen were sampled for Rb-Sr, K-Ar, Pb-Pb and U-Pb dating. The results of these early studies were tabulated in Walpole et al (1968). McDougall et al (1965) carried out Rb/Sr and K/Ar dating on sedimentary rocks and granites from the McArthur Basin. In 1972, BMR commenced Rb/Sr geochronological studies to date major tectonic events in the Arunta Region, but most results were not published until early 1980s (Black and Shaw 1995). Black (1977) carried out Rb/Sr geochronology of the granites and sedimentary rocks of the Tennant Region. At the time, it was generally thought that the Rb/Sr system was robust enough to withstand subsequent geological processes, unless melting had taken place.

However, by early 1980, it was realised that both Rb/Sr and K/Ar isotopic systems are easily reset by subsequent tectonothermal events and remain open until lower temperatures are attained, and therefore can record younger ages. Conventional U-Pb zircon geochronology is a most robust technique, but cannot be used for complex zircons containing inherited cores or metamorphic rims. The \(^{20}\text{Ar}/^{39}\text{Ar}\) technique, an adaptation of the K-Ar geochronological technique, is used for dating K-rich rocks and minerals (via the natural decay of \(^{40}\text{K}\) to \(^{40}\text{Ar}\)
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through a step-heating process. The method is more precise and accurate than the Rb/Sr method, but has similar resetting problems due to later thermal events.

The development of SHRIMP (Sensitive High Resolution Ion Micro Probe) dating in the early 1980s revolutionised geochronology through its ability to rapidly measure the isotopic and elemental abundances in minerals (most commonly U and Pb in zircon) at a micrometre-scale, making it well-suited for the analysis of complex minerals, particularly in metamorphic and igneous rocks. It also has allowed the rapid analysis of the age of detrital zircons from sedimentary rocks. Although limited SHRIMP work was undertaken on behalf of NTGS during the 1990s, it was not until the commencement of the NTGS–GA Geochronology Project under the National Geoscience Accord in 1999 that significant amounts of SHRIMP U-Pb data were routinely acquired in NTGS projects. Under the NTGS–GA collaboration, GA undertakes SHRIMP geochronology on behalf of NTGS, with the sharing of costs and intellectual property. In addition to the large volume of SHRIMP data generated under this scheme, NTGS has also undertaken Laser Ablation-Induced Coupled Mass Spectrometry (LA-ICPMS) geochronology since 2007, particularly for U-Pb analysis of detrital zircons, as well as Lu-Hf isotopic analysis of zircons to characterise their source. This new geochronological dataset has vastly improved the understanding of the NT’s geological framework, regional correlations and tectonic evolution.

GEOPHYSICAL SURVEYS

Airborne magnetic and radiometric surveys

Coverage of high-quality magnetic and radiometric surveys in the NT is shown in Figure 1.17. The first systematic geophysical surveys in the NT commenced in 1935 with the setting up by the Commonwealth Government of the Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA). Very early geophysical surveys were carried out in the Pine Creek, Redbank and Tennant Creek areas. Magnetic surveys in the Tennant Creek area were exceptionally successful in outlining the ironstone-hosted gold-copper-bismuth orebodies that are characteristic of this mining district (Rayner 2007). In the early to mid-1950s, BMR purchased a number of aircraft for the purpose of airborne geophysical surveys. In the Northern Territory, the first airborne radiometric surveys were carried out in 1952 over

Figure 1.17. Coverage of high-quality magnetic and radiometric surveys of the NT.
the Rum Jungle and Edith River areas of the Pine Creek Orogen (Milligan et al 1994, Wood and McCarthy 1952). Other areas covered by airborne radiometry during the 1950s included Mosquito Creek (Livingstone 1957), Mount Hardy, Nicholson River (Livingstone 1955), Gardiner Range (Muller 1961), Tennant Creek (Spence 1962) and South Alligator Valley (Livingstone 1958). Radiometric anomalies were recorded and classified as being first-, second- and third-order in terms of size and intensity. Most surveys were flown by traverses spaced between quartet of a mile to two miles by a large DC-3 aircraft at an elevation of about 500 feet (about 150 m). Lighter Cessna and Auster aircraft were used to better define anomalies picked up in the initial DC-3 surveys.

Both data quality and accuracy has improved since the first airborne geophysical surveys and techniques have benefited from technological advances in data acquisition, measurement precision and compensation systems for removing the magnetic effects of survey aircraft. Most of the historic radiometric surveys recorded data using just 4 channels, but radiometric recording of 256 channels of gamma ray data is now standard. The advent of GPS systems has been superseded by better-quality closely spaced surveys, while radiometric recording of 256 channels of gamma ray data is now a standard. The advent of GPS systems has been superseded by better-quality closely spaced surveys, most of the early surveys have now been superseded by better-quality closely spaced surveys, flown since 1981. All NTGS surveys have been conducted at a flight line spacing of 500 or 400 m, with the exception of the Bonney Well and Jervois surveys, and GA’s Tennant Creek survey, which were all conducted at a spacing of 200 m.

Since the start of the first airborne survey in the Rum Jungle area, GA has acquired magnetic/radiometric data over a million line km in the Northern Territory. GA’s contribution was fairly regular until 1977 and became intermittent thereafter, returning to very significant contributions in 1987, 1993 and 1998.

NTGS was one of the first of the Australian states and territories to acquire high-quality airborne regional geophysical survey data on a systematic basis. The first NTGS-sponsored survey was flown in 1981 over BARROW CREEK. It covered an area of 17280 km² on a line spacing of 160 m. In the sedimentary basins, the line spacing of surveys was usually greater than 300 m. A line spacing of 400 m or less and a flying height of 80 m or less is now standard and most of the early surveys have now been superseded by better-quality closely spaced surveys, flown since 1981. All NTGS surveys have been conducted at a flight line spacing of 500 or 400 m, with the exception of the Bonney Well and Jervois surveys, and GA’s Tennant Creek survey, which were all conducted at a spacing of 200 m.

From 1981 to 1999, NTGS gradually acquired regional geophysical data at an average rate of coverage of one 1:250 000-scale mapsheet per year. However from 1999, an appreciable acceleration of the airborne program was made possible through significant additional funding provided by the NT Government’s three successive exploration initiatives. This has enabled the proportion of the NT covered by modern airborne surveys to rise from 48% in 1998–1999 to more than 90% in 2012 (Figure 1.17).

Numerous geophysical surveys at various scales have also been flown across the NT by exploration companies. NTGS has developed a spatial index of open file company surveys, featuring comprehensive specifications of all surveys for which it holds digital data.

Gravity surveys

Coverage of high-quality gravity surveys of the NT is shown in Figure 1.18.

In 1960, BMR commenced a helicopter-supported 11 km-spaced regional gravity program for the Australian continent that took 15 years to complete. Until 1998, this was the only gravity dataset available for most regions of the NT. The first more detailed (4 km line spacing or less) surveys were the 1998 Tennant Creek and 1999 Tanami surveys by Geoscience Australia. Since 2003, NTGS has invested in significantly improving the gravity coverage of the NT, commencing with the West Arnhem survey (acquired using the airborne GT-1A method) and subsequent helicopter-supported ground gravity surveys. The ground gravity surveys have been significantly enhanced by exploration companies that have funded infill
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over their areas of interest. As of November 2012, 44% of the NT is covered by gravity surveys at a station spacing of 4 km or less, including the entire Tanami and Arunta regions, and large areas of the Amadeus Basin, northern Georgina Basin and southern McArthur Basin (Figure 1.18).

Other geophysical surveys

Numerous electromagnetic geophysical methods, such as electromagnetic (EM) and induced polarisation (IP) surveys have been used for exploration purposes in the NT, but the use of electrical methods in precompetitive geoscience is a relatively recent development. The only large precompetitive EM survey acquired to date is the Pine Creek airborne electromagnetic (AEM) survey, which was flown in 2008–2009 by GA, under their Onshore Energy Security Program. The survey included 29 900 line-kilometres of new data at various line spacings (555 m, 1666 m and 5000 m) covering 74 000 km², including large areas of the Pine Creek Orogen (excluding Kakadu National Park) and northwestern McArthur Basin (Craig 2011). Numerous regional-scale AEM surveys have also been acquired under the NTGS Geophysics and Drilling Collaborations program since 2010, particularly in central Australia, were they have been used in uranium exploration programs.

Multispectral and hyperspectral remotely sensed data are increasingly being used to understand the distribution of key minerals at the surface, particularly to understand alteration systems and regolith geology. In 2012, NTGS and CSIRO released sixteen Territory-wide mineral maps, based on a stitch of ASTER multispectral data. Small-scale airborne hyperspectral surveys have also been acquired in key regions of the NT. Incorporation of hyperspectral data into the third dimension is provided by the NTGS HyLogger™, which has been acquiring detailed hyperspectral information on drill core from across the NT since 2010.

A number of deep seismic surveys have been acquired by GA, particularly in the southern half of the NT. Notable deep seismic surveys include the Amadeus Basin (1985), Batten Fault Zone (2002), Tanami (2005) and Georgina–Arunta (2009) seismic traverses. These interpreted seismic lines have contributed greatly to the understanding of the NT’s deep crustal structure and tectonic evolution.

DEFINITIONS AND NOMENCLATURE

In general, the geoscientific terminology used in this volume follows definitions given in Fisher and Warren (1975), Plumb et al (1981) and the American Geological Institute’s Glossary of Geology (Neuendorf et al 2005). The following regional-scale geoscientific terms are frequently used in this volume, as defined below.

A craton is a part of the Earth’s crust that has attained stability and has been little deformed for a prolonged period of time. A sedimentary province (or basin) is an accumulation of sedimentary rocks, with or without volcanics, deposited in a subsiding segment of the Earth’s crust. Its lateral boundaries may be structural, depositional, erosional, or interpreted (in the sub-surface), and its vertical boundary is a regionally extensive unconformity. A platform is an area covered by relatively flat or gently tilted, mainly sedimentary rocks, usually overlying an orogenic domain (or orogen), which is an area characterised by intense deformation and widespread metamorphism. A geological region is defined as a relatively large two-dimensional geographical area with a cohesive, in some cases complex, geological assemblage that is significantly different in overall geology from the adjoining regions, and differs from geological province in that it does not include depth/time dimensions. Geological provinces are defined as three-dimensional bodies of rock with distinct geological characteristics and ages, that are separated from other provinces by major structures and/or unconformities. For example, the Tennant Region covers a large geographical area containing a wide spectrum of Proterozoic sedimentary, metamorphic and igneous rocks surrounded by younger Phanerozoic basins. This region is subdivided into three distinct geological provinces, namely the Warramunga, Davenport and Tomkinson provinces. An inlier is a relatively small geological area surrounded by younger rocks, whereas an outlier is a small geological area surrounded by older rocks.

Mapsheets nomenclature and locality reference

Names of 1:250 000 and 1:100 000 mapsheets are in large and small capital letters respectively, eg DARWIN, KOOLPINYAH. Locations cited in this publication are based on Map Grid of Australia (MGA) coordinates and the Geocentric Datum of Australia 1994 (GDA94). The grid zones covered by the Northern Territory are 52 and 53,
Table 1.1. Comparison of nomenclature of stratified and non-stratified rock (modified from Parker in Drexel et al 1993).

<table>
<thead>
<tr>
<th>NOMENCLATURE HIERARCHY</th>
<th>Sedimentary, lavas, pyroclastic rocks and metamorphic rocks with preserved stratigraphic layers.</th>
<th>High-grade metamorphic rocks with stratigraphic layers not preserved or not clearly established.</th>
<th>Intrusive igneous rocks and combined intrusive / extrusive igneous bodies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supergroup</td>
<td>eg Woodcutters Supergroup</td>
<td>Supersuite</td>
<td>eg Cullen Supersuite</td>
</tr>
<tr>
<td>Group</td>
<td>Complex</td>
<td>Suite</td>
<td>eg Jim Jim Suite, Kalkarindji Suite</td>
</tr>
<tr>
<td>Subgroup</td>
<td>eg Kombolgie Subgroup</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation</td>
<td>eg Wildman Siltstone</td>
<td>Geologic term + metamorphic term</td>
<td>Geologic term + lithological term</td>
</tr>
<tr>
<td>Member</td>
<td>eg Acacia Gap Quartzite Member</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stratigraphic nomenclature

The stratigraphic names used in this volume are listed in Geoscience Australia’s Stratigraphic Unit Database (http://www.ga.gov.au/products-services/data-applications/reference-databases/stratigraphic-units.html), which was originally established as the National Register of Stratigraphic Names in 1949. This database is a centralised reference point for all Australian stratigraphic unit information and it provides the primary national standards for geological nomenclature in Australia. Staines (1985) has published a guide to lithostratigraphic nomenclature in Australia on behalf of the Australian Stratigraphy Commission. Most Northern Territory geological units are named in accordance with the International Stratigraphic Guide (Murphy and Salvador 2000). However, there are some cases where informal stratigraphic names have been used and in such cases, the names are not capitalised (eg Inindia beds). Names in single quotes (eg ‘Horn Valley Formation’) have been superseded and are not current.

Rock terminology and classification

The naming hierarchy used in this volume for stratified rocks (sedimentary rocks, lava, pyroclastics and metamorphic rocks that preserve stratigraphy), metamorphic rocks and igneous rocks is provided in Table 1.1. Grain size terminology of clastic rocks follows Wentworth (1922). Sandstones are classified according to Folk (1974) and the carbonate rock classification follows the revision of Wright (1992). Igneous rock names follow the nomenclature scheme approved by the International Union of Geological Sciences (Le Maitre et al 1989).

Timescale

The International Commission on Stratigraphy (ICS) 2010 geological timescale is used in this volume. Listed numerical ages in this timescale are after Gradstein et al (2004) and Ogg et al (2008). Where Australian stage names are used (eg for the Cambrian and Ordovician), they are correlated against the ICS stages.

ACKNOWLEDGEMENTS

In the first instance, the authors of this compilation express thanks to all geologists of government, industry and academia who have advanced the geological understanding of the Northern Territory. It is their painstaking meticulous work that has made this publication possible. Apart from the contributing authors, many other staff of the Northern Territory Geological Survey have made very valuable suggestions and input leading to numerous improvements in the volume.

The seed of this publication was sown during the regime of Dennis Gee at the time of the publication of the 2.5M-scale Geological Map of the Northern Territory in 2001, but actual work on the volume was delayed until late 2005, when then-Director Richard Brescianini recognised the need for such a publication at a time when there was high staff turnover. We are indebted to both Dennis and Richard for pointing us in the right direction.

A great deal of the high-quality, recent U-Pb SHRIMP geochronology data referred to in this volume was collected through the collaborative NTGS-Geoscience Australia (GA) geochronology project since 1999, as part of the National Geoscience Agreement (NGA). GA are acknowledged for their significant economic and scientific contributions to studies of the geology of the NT.

A number of colleagues from the state geological surveys of Queensland, New South Wales, South Australia and Western Australia, and from the NT Department of Land Resource Management (formerly Natural Resources, Environment, the Arts and Sport) have reviewed chapters within this volume and/or have supplied information, images and diagrams. Their valuable contributions to this text are gratefully acknowledged. Many colleagues from the exploration and mining industry have also supplied helpful and constructive comments and information on various sections of the text, as well as a number of images and diagrams.

This first-ever detailed compilation on the geology and mineral resources of the Northern Territory has been greatly enriched by all of the above contributions.
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