Government of **Western Australia**
Department of **Mines and Petroleum**

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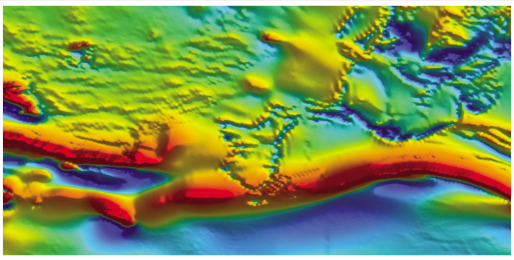
GSWA 2010 EXTENDED ABSTRACTS
Promoting the prospectivity of Western Australia



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25 February 2010

Geological Survey of Western Australia

MINISTER FOR MINES AND PETROLEUM
Hon. Norman Moore MLC

DIRECTOR GENERAL, DEPARTMENT OF MINES AND PETROLEUM
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EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Tim Griffin

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Welcome to GSWA 2010

GSWA 2010, the Geological Survey of Western Australia annual Seminar and Poster Display, provides an opportunity for geoscientists from the resources industry, from academia, and those involved in land use planning, to get an update on GSWA's latest activities and products through poster displays and technical presentations.

Our most recent precompetitive geoscience datasets remain focused on promoting mineral and energy exploration in the underexplored greenfields areas of the State. In April 2009, the Western Australian Government announced, as part of the Royalties for Regions initiative, funding of a five-year $80 million initiative entitled the Exploration Incentive Scheme (EIS) that is managed by GSWA. The highlights of the program for 2009–10 will be a major feature of GSWA 2010, with the release of more than 900 000 line km of airborne magnetic and radiometric surveys covering significant areas of the Eucla and Canning Basins, and the release of gravity surveys in the southern Yilgarn and Albany–Fraser regions.

Other programs being funded through EIS will feature prominently in the Poster Displays, including results from the first round of the Co-funded Exploration Drilling Program aimed at assisting mineral and energy explorers who are using innovative targeting methodologies in underexplored areas. A significant part of EIS funding will be used to develop cutting-edge 3D regional geoscience products using the newly acquired geophysical data, which will include deep seismic traverses and magnetotelluric surveys, integrated with traditional 2D geoscience studies.

Our ongoing programs will also be highlighted in the extensive Poster Displays and in the technical presentations. GSWA geoscientists will be available throughout the day to discuss the details of the geology and mineralization of their project areas and of the State as a whole, as well as other aspects of the Survey's activities, products, and services. We have again included poster displays from other geoscience agencies and research groups in Western Australia, including the Centre for Exploration Targeting (CET) at UWA, the Centre for 3D Mineral Mapping (C3DMM), and the John de Laeter Centre for Mass Spectrometry (JdeLCMS).

The technical presentations will emphasize the new datasets that have been released or are being acquired through EIS programs and through our ongoing programs. The enhancement of our geochronology program under EIS will be described, detailing new techniques and the acquisition of different isotopic datasets. As well as our staff presenters, Ned Stolz from Geoscience Australia will review progress of the Onshore Energy Security Program, discuss new programs, and present new pre-competitive datasets and interpretations of datasets already acquired in Western Australia. Stedman Ellis, the Deputy Director General of the Department of Mines and Petroleum, will look at changes to the approvals process and the Lead Agency role of DMP.

The presentations will be followed by a Panel Discussion with topics and questions sought from registrants. This is your opportunity to provide feedback on our programs and products, on how you use our information, and on the formats we use to provide it.

Tim Griffin
Executive Director
February 2010

GSWA 2010 SEMINAR PROGRAM — 25 FEBRUARY 2010

FREMANTLE

8.15 – 8.45	**REGISTRATION**	
8.45 – 8.55	**Welcome and opening remarks**	*Director General DMP: Richard Sellers and Executive Director GSWA: Tim Griffin*
8.55 – 9.20	Stratigraphic associations in the Eastern Goldfields Superterrane	*Steve Wyche*
9.20 – 9.45	Geology of the Lake Johnston greenstone belt, Youanmi Terrane, Yilgarn Craton	*Sandra Romano*
9.45 – 10.10	Enhanced geochronology and potential for understanding tectonics and mineralization	*Mike Wingate*
10.10 – 10.35	The GSWA HyLogger™: rapid spectral analysis and its application in detecting mineralization	*Lena Hancock*

Morning Tea 10.35 – 10.55

10.55 – 11.05		*Minister for Mines and Petroleum Hon. Norman Moore MLC*
11.05 – 11.25	Stimulating greenfields exploration and the Exploration Incentive Scheme (EIS)	*Tim Griffin*
11.25 – 11.50	Progress on the Co-Funded Drilling Program	*Margaret Ellis*
11.50 – 12.15	Delivering pre-competitive data for onshore energy exploration: Geoscience Australia programs in Western Australia	*Ned Stolz Geoscience Australia*

Lunch 12.15 –1.30

1.30 – 1.55	Geology and physical volcanology of the Bentley Supergroup, Musgrave Province	*Mario Werner and Heather Howard*
1.55 – 2.20	Reassessment of the geology and exploration potential of the Western Australian Amadeus Basin	*Peter Haines*
2.20 –2.45	Building the Proterozoic Albany–Fraser Orogen on the Yilgarn Craton margin: setting the scene for Tropicana	*Catherine Spaggiari*

Afternoon Tea 2.45 – 3.15

3.15 – 3.40	REE, lithium, potash, and phosphate mineralization in Western Australia	*Don Flint*
3.40 – 4.05	What do the changes to the approvals processes mean to the minerals exploration and mining sector?	*Deputy Director General Strategic Policy, DMP: Stedman Ellis*
4.05 – 4.30	**PANEL DISCUSSION**	

Sundowner 4.30 – 5.30

Contents

Stratigraphic associations in the Eastern Goldfields Superterrane

by

S Wyche, CE Hall, MJ Pawley, and KF Cassidy[1]

Various stratigraphic schemes have been applied in the Eastern Goldfields Superterrane, but most have been locally focused, or have been hampered by an inadequate understanding of structural and chronostratigraphic relationships. With the recent completion of 1:100 000-scale outcrop mapping by GSWA and Geoscience Australia, it is now possible to use the large amount of geophysical, geochemical, and geochronological data that have been generated over the past thirty years to implement a systematic stratigraphic scheme across the Eastern Goldfields Superterrane. Much of the new data have been acquired through industry-sponsored research that includes the pmd*CRC, and AMIRA and MERIWA projects.

New datasets

A large amount of geophysical data has been acquired since the 1980s, beginning with high-quality aeromagnetic data, followed by gravity and seismic data and, more recently, magnetotelluric data. Recent structural studies using these data in conjunction with the evolving detailed mapping (Blewett and Czarnota, 2007) have allowed a more holistic understanding of the structural history of the Eastern Goldfields and, in particular, have emphasized the role of extensional tectonics in the development of stratigraphic successions.

High-resolution U–Pb zircon geochronology was first used in the Eastern Goldfields in the 1980s, and systematic dating commenced with the building of the Perth Consortium Sensitive high-resolution ion microprobe (SHRIMP) in the early 1990s. Since then, a large amount of SHRIMP data has been acquired through both government- and university-led mapping and research projects. These data have been used to constrain deformation events, to place the different types of granite magmatism in their temporal context, to date specific parts of the stratigraphy, and to determine the maximum depositional ages and provenance histories of sedimentary successions.

Stratigraphic issues

Early work by CSIRO recognized that the komatiite volcanism in the western part of the Eastern Goldfields Superterrane (formerly called the 'Norseman–Wiluna greenstone belt') was possibly attributable to a single event (Hill et al., 1995). SHRIMP dating subsequently demonstrated that this komatiite event likely took place during a short time interval at about 2704 Ma (Kositcin et al., 2008; Geological Survey of Western Australia, 2010). Building on the locally recognized stratigraphy at Kalgoorlie (Woodall, 1965), Swager et al. (1995) developed a regionally extensive stratigraphy for their 'Kalgoorlie Terrane' based on the interpretation that the komatiite unit can be used as a regional marker horizon. Subsequent mapping and geochronology, such as the work of Fiorentini et al. (2005) in the Agnew–Wiluna area, have supported this interpretation and provided a basis for the description of 'Kalgoorlie Terrane' stratigraphy between Norseman and Wiluna.

However, while the geochronology has largely validated the interpretation of the Norseman–Wiluna komatiite event, new levels of complexity have been introduced into the stratigraphic characterization of the greenstones of the Eastern Goldfields Superterrane by the confirmation that felsic volcanism across the region is diachronous and that different volcanic centres have distinctive age and geochemical characteristics (Barley et al., 2008a). It has also been shown that, although ultramafic volcanism to the east of the Norseman–Wiluna komatiite at Murrin Murrin also occurred at about 2700 Ma, there is a significantly older (c. 2800 Ma) komatiite succession farther to the east at Windarra (Kositcin et al., 2008). Ages of other ultramafic units east of the Norseman–Wiluna komatiite are not well established but associations within greenstone belts suggest that there are other instances of older komatiite.

New geochemistry, accompanied by locally detailed mapping and volcanological studies, on major felsic volcanic centres (Barley et al., 2008a) and mafic and ultramafic successions (Barley et al., 2008b) throughout the Eastern Goldfields has led to the recognition of sedimentary and volcanic rock associations with different ages and chemical characteristics. This in turn has resulted in the interpretation of a number of fault-bound terranes to the east of the original Kalgoorlie Terrane. Not all authors agree in detail on the criteria for assigning of components to the various terranes in all cases (Kositcin et al., 2008; Cassidy et al., 2006). However, new Sm–Nd datasets that show underlying mantle extraction ages across the Yilgarn Craton provide a strong basis for the broad subdivision of the terranes as they are presently understood (Champion and Cassidy, 2007). These studies are currently being supplemented by new Lu–Hf analytical work.

Recent studies (Krapež, 2008) have indicated a complex interplay between tectonic processes and the resulting

[1] Bare Rock Geological Services Pty Ltd

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Figure 1. View looking east from the summit of Mount Hunt across the Kalgoorlie mafic–ultramafic stratigraphy towards Serpentine Bay and Hannan Lake.

stratigraphic elements, for example the development of the so-called 'late basins'. It is likely that systematic compilation of mapping, geochemical, and geochronological data, together with an improved understanding of the structural and stratigraphic architecture, will demonstrate that the various terrane components have more complex internal structure than is presently recognized. For example, Tripp et al. (2007) have shown in the Kalgoorlie area that there are considerable facies variations across major faults, some of which were recognized as 'domain boundaries' by Swager et al. (1995). Thus, these faults may represent relatively early structures that have affected the basin development. Elsewhere, implementation of stratigraphy may highlight components of greenstone belts that appear to be out of context with the known geology of the terrane in which they occur. For example, the banded iron-formation and ultramafic rocks along the western side of the northern end of the Yandal greenstone belt (the Moilers Domain within the Kalgoorlie Terrane of Cassidy et al., 2006) may prove to be a fragment of an older terrane (e.g. the Youanmi Terrane to the west or the Burtville Terrane to the east).

Implications

A well-founded and formal application of stratigraphic concepts in the Eastern Goldfields is now possible and has the potential to bring fresh ideas to mineral exploration in the region. This is self-evident for nickel deposits where the distribution of the host komatiites, proximity to volcanic vents, and the nature of the rocks onto which komatiites were deposited, or into which they were intruded, are all important factors in determining exploration targets (Barnes, 2006). Similarly, for volcanogenic massive sulfide deposits, the mapping and characterization of the felsic volcanic complexes will assist in understanding known deposits, and in identifying areas worthy of further attention. While there are many factors that affect the distribution of gold deposits, recent work has shown that the recognition and characterization of sedimentary facies such as the sedimentary rocks of the Black Flag Group and those in the 'late-basin' successions are significant factors in the development of successful mineralization models (Squire et al., 2007; Hall, 2007).

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Geology of the Lake Johnston greenstone belt, Youanmi Terrane, Yilgarn Craton

by

SS Romano and MP Doublier

Greenstones in the southern part of the Southern Cross Domain in the central Yilgarn Craton (Fig. 1) host a range of significant mineral deposits including gold (e.g. Marvel Loch), iron (Koolyanobbing), and nickel (Emily Ann, Maggie Hays, Forrestania greenstone belt). A new Geological Survey of Western Australia mapping program in the region is reassessessing the established stratigraphic setting of the greenstone belts and, through an ARC Linkage project being undertaken with scientists from The University of Western Australia, investigating the structural and metamorphic setting of the Southern Cross greenstones with a view to generating a tectono-metamorphic model of the region.

Regional setting

The Lake Johnston greenstone belt (Fig. 1) is the most southeasterly greenstone belt in the Southern Cross Domain of the Youanmi Terrane. The Southern Cross Domain is bounded to the west by the Murchison Domain and South West Terrane, and separated from the Eastern Goldfields Superterrane to the east by the crustal-scale Ida Fault. Recent work by Van Kranendonk and Ivanic (2009) established a regional stratigraphic scheme for the northern Murchison Domain, which is characterized by three volcanic cycles between c. 2820 and c. 2600 Ma. However, there is widespread evidence of older magmatic activity in the Murchison region dating back to c. 3000 Ma. The greenstones of the Kalgoorlie Terrane, the westernmost terrane of the Eastern Goldfields Superterrane, are dominantly 2710 to 2660 Ma volcano-sedimentary successions (Kositcin et al., 2008).

Lake Johnston greenstone belt

Gower and Bunting (1976) published a stratigraphic succession for the Lake Johnston greenstone belt consisting of the Maggie Hays Formation at the base, overlain by the Honman Formation, with the Glasse Formation at the top.

The lowest exposed level of the Maggie Hays Formation, a submarine volcanic succession, is a thick package of strongly deformed pillowed and massive basalts that are overlain by a mixed sequence of hyaloclastite, basaltic lava flows, and tuffite. Thin, quartz-rich sedimentary interlayers become more abundant towards the top. The mafic rocks are intruded by ultramafic rocks, dolerite sills, and aligned pods and sills of pyroxenite, gabbro, and leucogabbro. A genetic connection to the vanadium-bearing Lake Medcalf layered intrusion in the southern part of the greenstone belt is possible, but has not yet been investigated. It is also possible that the ultramafic rocks of the Maggie Hays Formation are related to those that intrude the Honman Formation (see below) but this is yet to be demonstrated.

Most previous work has focused on the Honman Formation, which hosts the nickel deposits at Maggie Hays and Emily Ann. Porphyritic intermediate rocks, interpreted as volcanic rocks in the Honman Formation, yielded SHRIMP U–Pb zircon ages of 2921 ± 4 Ma and 2903 ± 5 Ma (Wang et al., 1996). An additional small zircon population of c. 2856 Ma, with high Th/U ratios of 5, was initially interpreted by Wang et al. (1996) to be of metamorphic origin. More recent studies suggest that zircons with Th/U ratios above 0.2 are igneous (Hoskin and Black, 2000), so the older zircon populations might be xenocrystic, and the age of extrusion c. 2856 Ma or younger. Further evidence for a younger age for the Honman Formation is given by felsic volcaniclastic rocks within the formation that have a maximum depositional age of c. 2873 Ma (Thebaud et al., 2009).

Wang et al. (1996) interpreted the komatiite unit within the dated porphyritic intermediate rocks to be extrusive, and therefore considered that the ages of the intermediate rocks constrained the age of komatiites within the Honman Formation. Thus, the Emily Ann and Maggie Hays nickel deposits have been cited as examples of old (>2900 Ma) komatiite-hosted nickel deposits (Barnes, 2006). However, recent mapping supports drillcore studies by Heggie et al. (in press) which showed that, while there are ultramafic rocks present at all levels in the Honman Formation, extrusive (i.e. olivine spinifex-textured) komatiites are found only at the top of the formation. As the intermediate and felsic volcanic and volcaniclastic rocks underlie, or are intruded by, the komatiites, they must pre-date these ultramafic rocks.

The Honman Formation is overlain by the Glasse Formation, characterized by massive basalt with several amygdale-rich horizons, and minor ultramafic intrusive rocks. The context of the ultramafic rocks within the Glasse Formation is unclear. Although new mapping has not yet been completed on the formation, it is similar in character to the Maggie Hays Formation and aeromagnetic images show complexity that may indicate structural repetition.

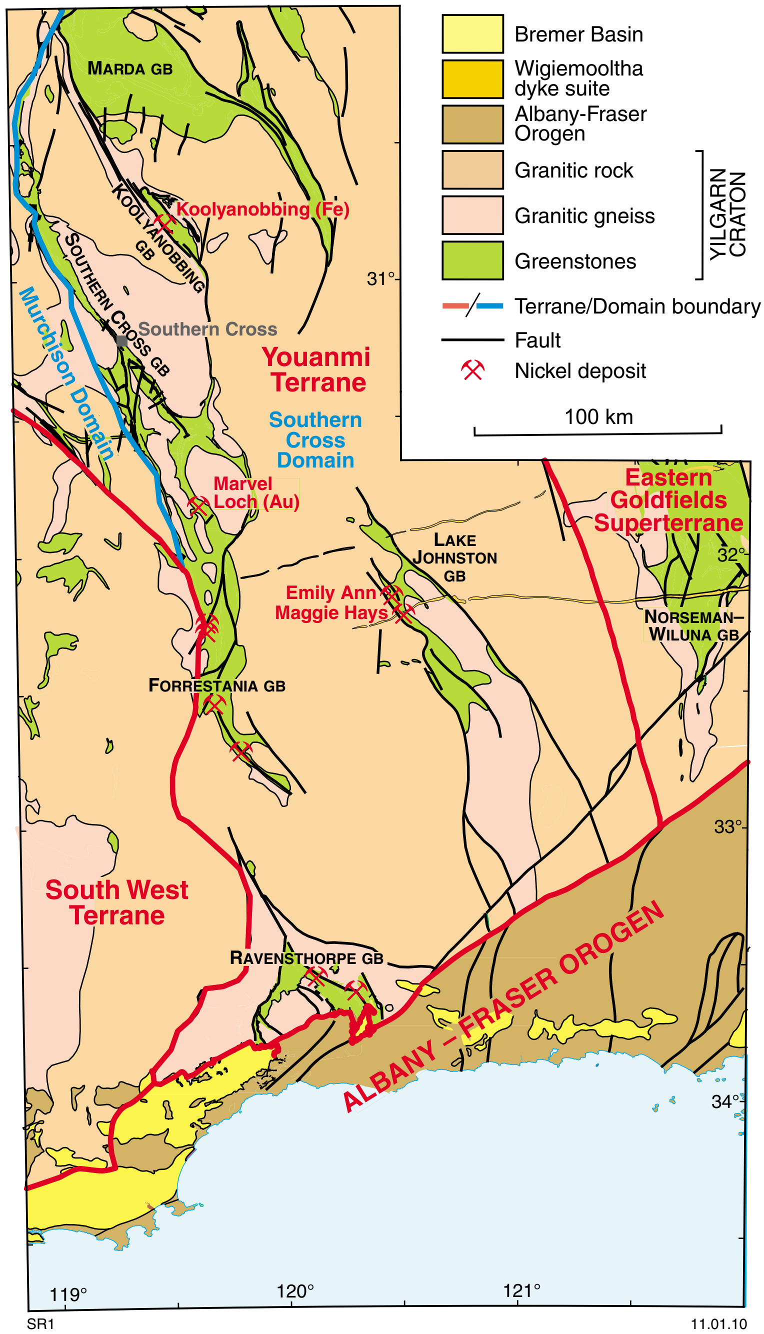

Figure 1. Geological map of the south Yilgarn (modified from the State 1:500 000-scale geology). The greenstone belts referred to in the text have been labelled (GB). The tectonic subdivision of the Yilgarn Craton is based on Cassidy et al. (2006).

Southern Cross greenstone belt

In the Southern Cross greenstone belt, porphyritic micrograntes that intrude the mafic–ultramafic succession yielded ages of 2912 ± 5 Ma and 2934 ± 7 Ma (Mueller and McNaughton, 2000). However, a recent age of 2702 ± 17 Ma for quartzofeldspathic sedimentary rocks (Thebaud and Miller, 2009), interpreted as a maximum age of deposition, showed that the belt also contains a much younger component, which has not been previously recognized. The provenance, geological context, and maximum age of deposition for these sedimentary rocks are still poorly constrained. They appear to be slightly younger than the sedimentary rocks of the Diemals Formation (2729 ± 9 Ma; Nelson, 2001a) and felsic volcanic rocks of the Marda Complex (2732 ± 3 Ma; Nelson, 2001b) to the north and may be derived, at least in part, from rocks similar in age to the major magmatic event associated with komatiite volcanism in the Kalgoorlie Terrane to the east (Kositcin et al., 2008). Whatever the case, the data suggest a substantial depositional hiatus in the Southern Cross greenstone belt.

Regional significance

Already the reappraisal of the stratigraphy of the Lake Johnston greenstone belt suggests that early interpretations of the age and setting of the Maggie Hays and Emily Ann nickel deposits may need to be revised. One consequence of this is that the assumed age of the nickel deposits in the Forrestania greenstone belt to the west may also need reconsideration. The relatively young age (c. 2702 Ma) for sedimentary rocks in the Southern Cross greenstone belt suggests the possibility that greenstone belts in the Southern Cross Domain contain previously unrecognized younger successions, including successions that are the same age as nickel-bearing komatiites in the Eastern Goldfields.

The limited amount of geochronological control in the Lake Johnston and Forrestania greenstone belts provides little evidence of direct correspondence between magmatic events in the southern part of the Southern Cross Domain and the volcanic cycles in the Murchison Domain.

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ROYALTIES FOR REGIONS
EXPLORATION INCENTIVE SCHEME

Enhanced geochronology and potential for understanding tectonics and mineralization

by

MTD Wingate and CL Kirkland

Knowledge of the age of rocks and tectonic events is fundamental to understanding geological evolution and the timing of mineralizing events. The Geological Survey of Western Australia routinely determines the ages of rocks by measuring the ratios of uranium, thorium, and lead isotopes in crystals of zircon and other minerals using the Sensitive high resolution ion microprobe (SHRIMP). Additional funding from the Exploration Incentive Scheme (EIS) has enabled GSWA to build on its existing strengths and expertise in geochronology, with the addition of in situ dating of phosphate minerals, Sm–Nd isotope analysis of whole rocks, and Lu–Hf isotope analysis of individual zircon crystals. These data can greatly enhance the understanding of geology and mineral potential in underexplored parts of Western Australia. In concert with these developments, substantial changes aimed at making results easier to access and more rapidly available, are improving the delivery of geochronology and other isotope data.

U–Pb zircon and baddeleyite geochronology

Dating of zircon and baddeleyite continues to be an essential component of GSWA's geochronology program. In 2008–09, more than 100 rock samples were processed at GSWA's laboratory for dating, with more than 90 samples dated by ion microprobe. These samples were collected to support GSWA mapping programs in the west Musgrave Province, Murchison Domain, Eastern Goldfields, eastern Yilgarn Craton, and the Capricorn and Albany–Fraser Orogens, and have yielded significant results.

A new regional geochronology dataset for the eastern Albany–Fraser Orogen indicates that a 1690 to 1660 Ma magmatic and sedimentary terrane, the Biranup Zone, extends for at least 1200 km along the southern and southeastern margin of the Yilgarn Craton (Spaggiari et al., 2010, this volume). These data also show that the Biranup Zone underwent a previously unrecognized deformation event at c. 1680 Ma (Kirkland et al., 2010). Such regional age information is not only critical in placing mineralizing events — such as the one that formed the significant Tropicana gold deposit — in their geological context, but also helps to identify areas that may have been subjected to similar episodes of mineralization.

Although the majority of gold, nickel, and platinum group element (PGE) deposits in Western Australia are hosted within mafic igneous rocks found in greenstone belts, few of these rocks have been dated directly, and most age constraints are indirect, involving the dating of crosscutting granites or detrital zircons in associated sedimentary rocks. Recent baddeleyite and zircon dating of leucogabbros in the northern Murchison Domain (where mafic–ultramafic rocks in layered intrusions make up about 40% by volume of greenstones) have defined four late Archean mafic suites, which host both vanadium and nickel–copper–PGE mineralization. In addition, this magmatism was in part coeval with mafic–ultramafic magmatism in the Burtville Terrane of the Eastern Goldfields Superterrane, suggesting the possibility of a shared history. Another example of direct dating of mineralization comes from a copper-mineralized dyke in the western Musgrave Province, which yields a U–Pb zircon age of c. 1070 Ma. This constrains the age of mafic magmatism associated with significant orthomagmatic Ni–Cu–PGE mineralization in the province (e.g. Nebo–Babel deposit).

In situ phosphate geochronology

Techniques for in situ dating of minerals in polished thin sections enable textural relationships between rock fabrics (i.e. deformation) and mineral growth to be put in a temporal context. Supported by both EIS and an Australian Research Council (ARC) Linkage grant, GSWA is collaborating with Curtin University of Technology, to apply in situ dating (Fig. 1) of a range of minerals (mainly monazite and xenotime) to regional- and deposit-scale field mapping. Although the magmatic and high-temperature metamorphic history of the Capricorn Orogen is reasonably well-defined by zircon geochronology, little is known about low- to moderate-temperature events such as sediment deposition, early diagenesis, low-grade regional metamorphism, and hydrothermal fluid flow and mineralization. Initial results from metasedimentary rocks include a range of monazite ages between c. 1550 and 1000 Ma. Samples have also

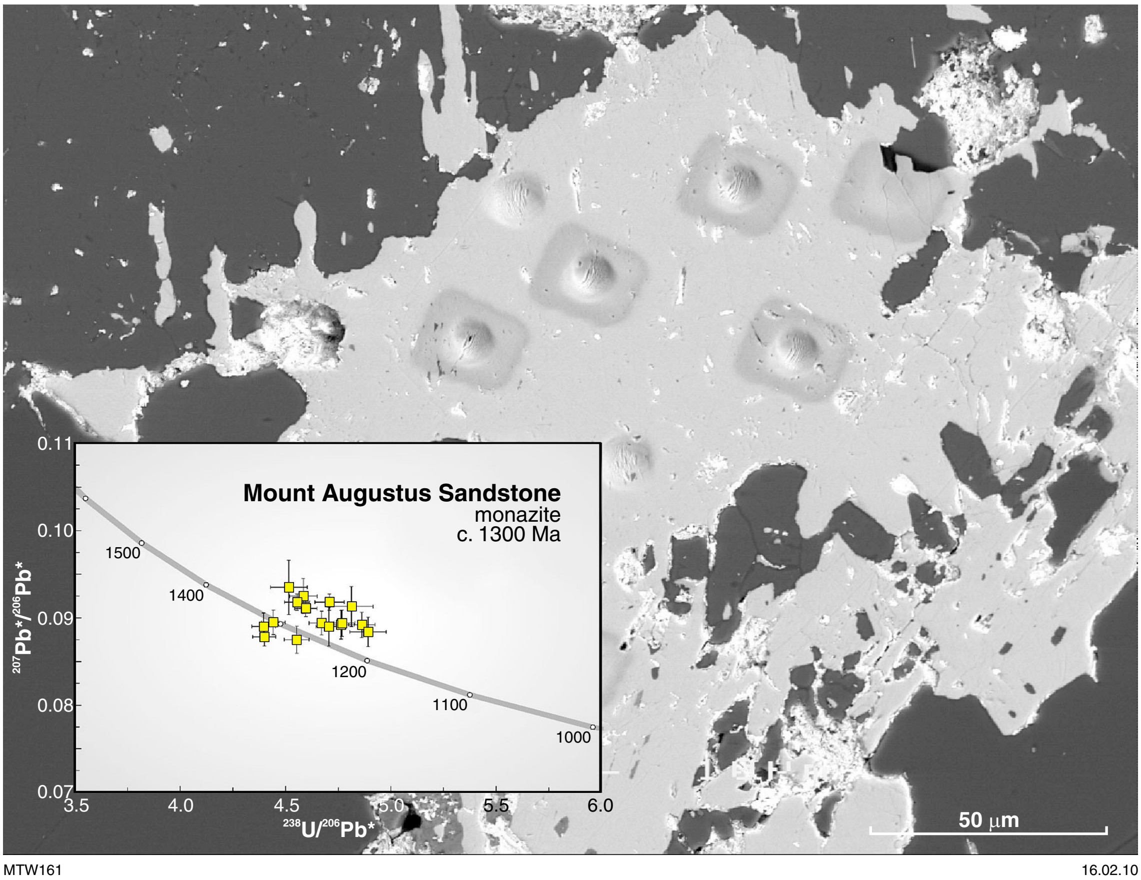

Figure 1. Backscattered electron (BSE) image of ion microprobe (SHRIMP) analysis craters in metamorphic monazite within a thin section of Mount Augustus Sandstone. Note the small size (<10 microns) of the analysis sites. The inset shows preliminary analytical results that indicate an age of about 1300 Ma. These and other analyses are helping to define a regional hydrothermal event at about 1300–1250 Ma that may have been responsible for widespread base metal mineralization in the Capricorn Orogen. Photomicrograph from Birger Rasmussen, Curtin University of Technology.

been collected to date rare earth element (REE)-bearing pegmatites using monazite and columbite–tantalite. In situ phosphate geochronology is expected to lead to a new understanding of tectonic events in the Gascoyne Province and Bangemall Supergroup, and will enable more effective exploration targeting.

Whole-rock Sm–Nd analyses

Insights into the nature of tectonics and crust–mantle interaction can be gained by studying Sm–Nd isotopes. To understand crustal evolution, knowledge of not only the age distribution of magmatic rocks but also of their sources (e.g. mantle-related or recycled older crust) is needed. Measurement of whole-rock $^{143}Nd/^{144}Nd$ can provide an estimate of when a melt was separated from a mantle source (or in complicated crustal source regions, an average mantle extraction age of all source components). In the Yilgarn Craton, Sm–Nd results have demonstrated a close spatial association between source domains of differing isotopic composition, age, and mineralizing events (Champion and Cassidy, 2007). Reconnaissance data available for parts of the Yilgarn Craton show that areas of different Nd model ages correspond to tectonic subdivisions, indicating that Sm–Nd isotope measurements can be used to map crustal age domains. Some younger 'juvenile' domains in the Youanmi and Kurnalpi Terranes are spatially related to known VHMS deposits, such as Golden Grove and the Teutonic Bore and Jaguar deposits. Under EIS, about 130 samples will be analysed each year for four years, mainly from mafic and intermediate rocks for which there are no U–Pb zircon data.

Zircon Lu–Hf analyses

In addition to providing crystallization ages, isotopic analysis of zircons can also elucidate the composition of the magma from which the zircons crystallized. Lu–Hf isotopes in zircon can be used in a similar manner to Sm–Nd, but with several key advantages. Owing to its extreme durability, zircon can survive geological recycling and retain information from early Earth history. The Lu–Hf system in zircon is also more resistant to disturbance than the Sm–Nd or U–Pb systems, and therefore has the potential to accurately retain information on the geological evolution of highly metamorphosed terranes. Lu–Hf analyses will include detrital zircons in sedimentary rocks, as well as zircons with multiple growth stages, which allow complex histories in both igneous and metamorphic rocks to be examined. About 1500 zircons, representing a large number of samples, can be analysed each year during EIS. The Lu–Hf analyses are conducted by the Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC) at Macquarie University. The project is adding considerable value to the existing GSWA geochronology dataset, and will promote understanding of geological evolution at a regional scale.

For example, Lu–Hf analyses have been employed to evaluate the tectonic evolution of part of the Arunta Orogen. Based on the apparent absence of inherited zircons of appropriate age, the Warumpi Complex of the Arunta Orogen has been interpreted as exotic to the North Australian Craton (NAC), and the c. 1690 to 1670 Ma Argilke magmatic event has been attributed to an outboard magmatic arc. However, new Hf isotopic data indicate that crustal residence ages of Argilke intrusions are similar to those in the Aileron Province of the NAC, and also extend to more juvenile values. This may be more compatible with northward subduction along the southern Aileron Province margin or the incorporation of Aileron sediments in Argilke magmas. The absence of zircon inheritance can be explained by zirconium undersaturation, thermal reworking, or sampling bias.

Acknowledgement

U–Pb isotopic analyses were conducted using the SHRIMP ion microprobes at the John de Laeter Centre for Mass Spectrometry at Curtin University of Technology, in Perth, Australia.

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The GSWA HyLogger™: rapid spectral analysis and its application in detecting mineralization

by

EA Hancock and JF Huntington[1]

Introduction

HyLogging™ is a new, highly automated system designed by CSIRO to determine drillcore mineralogy using rapid reflectance spectroscopy. The resulting data, coupled with simultaneous acquisition of high-resolution digital photographs of scanned core, can provide new insights into host-rock and alteration mineralogy, vectors to mineralization, objective determination of lithostratigraphic units and their boundaries, and refined inputs to resource block modelling and geometallurgical characteristics. All mineralogical and image data are stored on a central database, which can be accessed using the internet.

The GSWA HyLogger™, which was installed in July 2009 at the Carlisle Core Library, is one of seven machines in Australia that together make up the AuScope National Virtual Core Library (NVCL) consortium. This is a collaborative Federal and State project which aims to provide drillcore mineralogical and image data in a standard format.

Since the installation of the HyLogger in July 2009, about 7000 m of mineral and petroleum core have been scanned, and the data successfully processed.

Methodology

Drillcore is scanned in its original trays and requires minimal preparation, other than being dry and clean. Required metadata include hole location and depth.

The HyLogging system comprises an integrated suite of spectroscopic, imaging, lighting, and materials handling tools that enable core to be scanned semi-automatically. Scanning is carried out using a computer-controlled table that continuously moves the core in a zigzag path beneath the scanner at a rate of approximately one metre every 30 seconds.

The HyLogger currently uses a CDI silicon-array grating spectrometer for the visible near-infrared (VNIR) wavelengths (380 to 1000 nm), and a Fourier transform infrared (FTIR) spectrometer for the shortwave-infrared (SWIR) wavelengths (1000 to 2500 nm). Both spectrometers measure radiance that is converted to spectral reflectance in relation to a Spectralon standard. The raw spectrometer instantaneous-field-of-view is 8 mm in diameter. The imaging system is a digital three-colour (red, green, blue) area-array camera used in a line-scan mode with a resolution of 0.1 mm. The system constructs a continuous image of the core, frame by frame, as the tray passes underneath. The system incorporates a laser profilometer used to measure the physical condition of the core every 0.1 mm as well as fractures and breaks to assist in geotechnical assessment and for control of other aspects of the system. The spectrometer, image, and profilometer data are captured simultaneously during a single traverse of the core tray.

Depending on core diameter and tray size, one tray can be scanned in three to five minutes, meaning that more than 500 m of core could be measured in one day, though a more typical output is 300 m.

Software and processing

The HyLogging hardware is complemented by special CSIRO-developed software 'The Spectral Geologist' (TSG-Core™) for the analysis, mineralogical interpretation, and simultaneous visualization of the spectral, image, and mineralogical data. Identification of minerals is made using an updated version of 'The Spectral Assistant' (TSA™) algorithm, along with estimates of their relative proportions and an interpretation error.

Pre-processing of data imported into TSG-Core includes trimming imagery to reduce dataset size, applying masks to hide non-geological materials, depth logging, checking and editing erroneous classifications, creating new numeric scalars to highlight additional mineralogical properties of the core, and importing external information, such as lithological logs and assays. The TSG-Core process results in a series of numeric and graphic logs and output products that can be printed, converted to PDF files, or placed into the NVCL relational database. The processed dataset is about 3 megabytes/metre whereas the size of the raw dataset is about 5–7 times greater. Raw (non-TSG) data, referred to as Level 0, are archived, whereas the processed (TSG) data

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are referred to as Levels 1–5 depending on the stage of the processing applied.

A free version of TSG (TSG-Viewer) is available for examining previously processed datasets from www.thespectralgeologist.com.

Targeting minerals

The current version of the HyLogger is suited to the recognition of iron oxides, sulfates, hydroxyl- and carbonate-bearing minerals (Table 1). It is not designed for ore minerals, although some massive phases can be mapped.

A next-generation system, which will involve the addition of a thermal infrared (TIR) spectrometer (wavelengths from 6000 to 14000 nm), is designed for the detection of non-OH-bearing silicates, such as feldspar, pyroxene, olivine, garnet, and quartz.

Dark samples, small particle sizes, organic matter, coatings, and complex mixtures pose challenges for automated interpretation systems and can lead to TSA errors (Clark, 2004). Tools are provided to identify and edit these errors.

Applications for exploration

A goal of the HyLogging methodology is to improve the objectivity of drillcore logging, and increase the amount, quality, and value of information obtained from what is seen as an expensive type of exploration activity. Other exploration benefits (Huntington, 2007) include understanding:

- Signatures of mineralized environments — alteration types and zones
- Characteristics of primary rock types
- New vectors to mineralization
- Indicators of weathering regimes and processes
- Indicators of chemistry and temperature
- Metallurgical and geotechnical properties
- Differences between transported and residual materials in regolith.

The goal of the AuScope NVCL project is to make this new type of mineralogical drillcore information widely available for all forms of Earth science research and to unlock previously unrecognized information in the many public core libraries around Australia.

Petroleum core

Using the HyLogging methodology for petroleum core is a new direction for GSWA. Recently acquired spectral data for several kilometres of petroleum core from the Canning Basin has provided information about lithostratigraphic unit boundaries, porosity, and water content, which will assist in exploration targeting.

Case study (Minnie Springs molybdenum mineralization)

The Minnie Springs molybdenum–copper prospect is located in the Ti Tree Shear Zone, which cuts granitic rocks of the Minnie Creek batholith in the Gascoyne Province of Western Australia (Pirajno et al., 2008). Two mineralization styles are present: disseminated molybdenite in potassic-altered granite, and molybdenite-bearing quartz veins and veinlets hosted in sericitized foliated granite.

Table 1.TSA mineral database

	Group of minerals	*Mineral*
VNIR spectrometer		
	Iron oxide	Hematite, goethite, jarosite
SWIR spectrometer		
	Kaolin	Kaolinite WX (well-crystalline), kaolinite PX (poor-crystalline), dickite, nacrite
	White mica	Muscovite, phengite, paragonite, illitic muscovite, illitic phengite, illitic paragonite
	Smectite	Montmorillonite, nontronite
	Other AlOH	Pyrophyllite, gibbsite, palygorskite, diaspore
	Chlorite	Mg-bearing chlorite, Fe-bearing chlorite, intermediate Mg/Fe chlorite
	Dark mica	Biotite, phlogopite
	Mg clay	Incorporating saponite, hectorite, sepiolite
	Amphibole	Hornblende, tremolite, actinolite, reibeckite
	Serpentine	Serpentine (antigorite, chrysotile, lizardite)
	Other MgOH	Talc, brucite
	Sulfate	Jarosite, Na-bearing alunite, NH-bearing alunite, gypsum
	Epidote	Epidote, clinozoisite, zoisite
	Silicate	Prehnite, topaz, opal
	Tourmaline	Tourmaline, rubellite
	Carbonate	Calcite, dolomite, magnesite, ankerite, siderite

SOURCE: modified after Huntington et al. (1997)

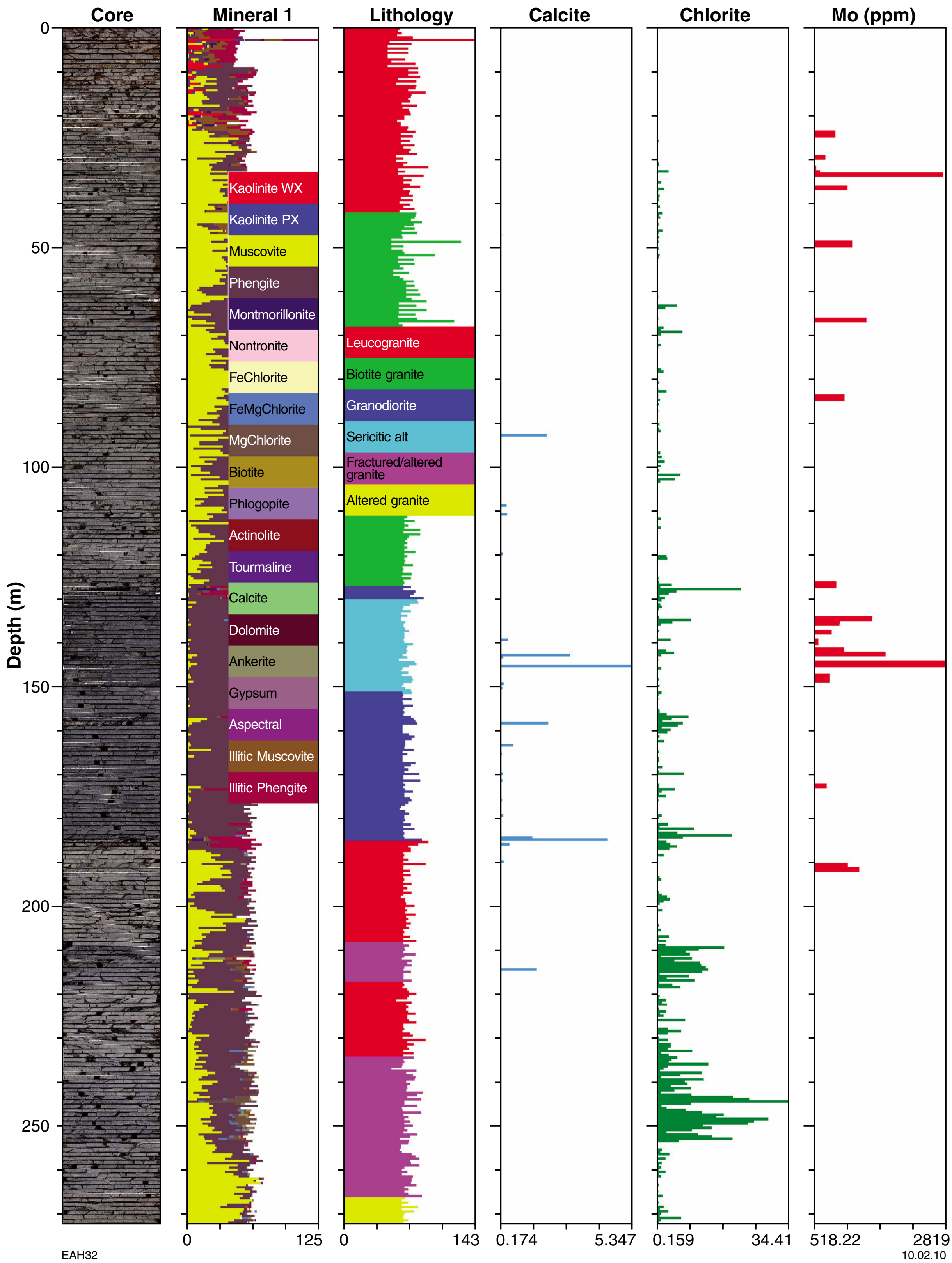

Figure 1. TSG graphic logs for drillhole MSD 2 (counts per 0.5 m core)

Three drillholes (118 m, 272 m, and 150 m depth, respectively) from the Minnie Springs prospect were scanned by the HyLogger. White mica, chlorite, and kaolinite were identified as the dominant minerals in the system, with calcite as a common secondary mineral in veins (Fig. 1). Minor minerals include tourmaline, zoisite, epidote, amphibole, nontronite, and montmorillonite. Subtle changes in the chemistry and crystallinity of muscovite/phengite/illite or Fe–Mg/Mg chlorite reflects varying physico-chemical properties. The pervasive development of low-Al phengitic white mica and chlorite reflects a low-temperature Fe–Mg-rich alteration environment that probably overprinted an early stage of sericitic (muscovite) formation. These sericitic and propylitic alteration assemblages are spatially associated with quartz–pyrite–molybdenite veins that are tracked by illitic phengite and calcite. The higher temperature potassic alteration is the earliest hydrothermal event in the system.

Conclusion

Considerable value can be added to drillcore information using HyLogger technology, which offers rapid and objective analysis, resulting in data that can be processed to indicate areas of mineralization or mineralization-related alteration. Provision of these data from a centralized database through the internet results in wider utilization of information and communication to a much broader community.

Acknowledgments

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ROYALTIES FOR REGIONS
EXPLORATION INCENTIVE SCHEME

Stimulating greenfields exploration and the Exploration Incentive Scheme (EIS)

by

TJ Griffin

In April 2009 the Western Australian Government announced Royalties for Regions funding for the five-year $80 million Exploration Incentive Scheme (EIS) to encourage exploration in Western Australia for the long-term sustainability of the State's resources sector. EIS is managed by the Geological Survey of Western Australia, and the work program over the period 2008–09 to 2012–13 will be dominated by pre-competitive geoscience programs. The progress of the signature Co-funded Government–industry drilling program to assist mineral and energy explorers using innovative targeting methodologies in WA's underexplored greenfields areas, is described elsewhere (Ellis, this volume). About $24 million of the funding will be of direct benefit to petroleum and energy explorers with the remainder primarily benefiting mineral explorers. The additional funds will ensure that GSWA remains firmly focused on encouraging mineral and energy exploration in underexplored greenfields areas of the State.

EIS has positioned GSWA to significantly increase its capacity to collect, interpret, and distribute up-to-date, relevant, high-quality pre-competitive geoscience datasets to the resources exploration industry in WA. It will allow us to apply new technologies to meet many of our objectives at a much faster rate than previously expected, and also to introduce emerging geoscience concepts and skills for underexplored regions in WA, as well as regions of known mineralization.

A focus for the acquisition of pre-competitive data will be the completion of the airborne magnetic and radiometric coverage of WA at 400 m line-spacing or better. This is long overdue, and equivalent data are generally available for other jurisdictions in Australia. The initial focus for 2008–09 and 2009–10 has been on northern Australia and the Eucla Basin. Nine surveys have been completed with six covering the central and northern Canning Basin and the adjacent Proterozoic basement of the Paterson Orogen in the east Pilbara and the King Leopold Orogen in the west Kimberley (Fig. 1). The remaining three, flown at half the usual spacing of GSWA's regional surveys, give a remarkably detailed picture of Proterozoic basement rocks buried beneath sand and the relatively thin Cenozoic limestones of the Eucla Basin, as shown on Figure 1. Drillcore from Gunson Resources' Burkin Nickel Project and Teck Australia's Big Red and the Serpent Project, funded under the EIS Co-funded Government–industry drilling program, will help to further characterize the nature of these prospective rocks in what is clearly an underexplored part of WA.

The Kidson–Paterson deep-crustal seismic traverse will cross the Kidson Sub-basin of the Canning Basin, a frontier basin for hydrocarbon exploration. The traverse will be jointly funded with Geoscience Australia as part of their Onshore Energy Security Program (Stolz, this volume), and GSWA's contribution will be to ensure that the Proterozoic rocks of the Paterson Orogen are imaged. They contain world class gold–copper mineralization at Telfer, copper at Nifty, and uranium at Kintyre. Two further deep-crustal seismic traverses are planned for 2010–11, the first crossing the Paleoproterozoic and Mesoproterozoic rocks of the Capricorn Orogen between the Archean Pilbara and Yilgarn Cratons as part of a traverse co-funded with AuScope. The second, entirely funded under EIS, will cross the Narryer and Youanmi Terranes of the Yilgarn Craton. GSWA is collaborating with the Centre for Exploration Targeting (CET) to carry out a magnetotelluric (MT) survey from Hyden to Norseman, which crosses the southern part of the Southern Cross Domain and will image the Ida Fault at the boundary of the Youanmi Terrane with the Kalgoorlie Terrane. A further survey is planned in the Musgrave Province. MT surveys will be carried out in conjunction with the planned deep seismic traverses.

Ground gravity surveys at 2 km and 2.5 km spacing have been carried out around Cunderdin (including the Kauring Airborne Gravity Test Range) and the southeast margin of the Yilgarn Craton. Surveys are planned for the Southern Cross and Lake Johnston areas and the Gascoyne Province. There will also be a considerable expansion of our other datasets, with improved coverage of geology and regolith map layers planned in the Capricorn Orogen and in the Kimberley region. Soil-geochemistry surveys will target the northern and eastern margins of the Yilgarn Craton where deep weathering, regolith cover, and thin sedimentary basins obscure prospective Archean and Proterozoic bedrock.

GSWA will enhance our long-standing partnership with the John de Laeter Centre for Mass Spectrometry (JdeLCMS) to take advantage of expertise in SHRIMP phosphate geochronology developed at Curtin University and UWA to improve our understanding of very low- to moderate-

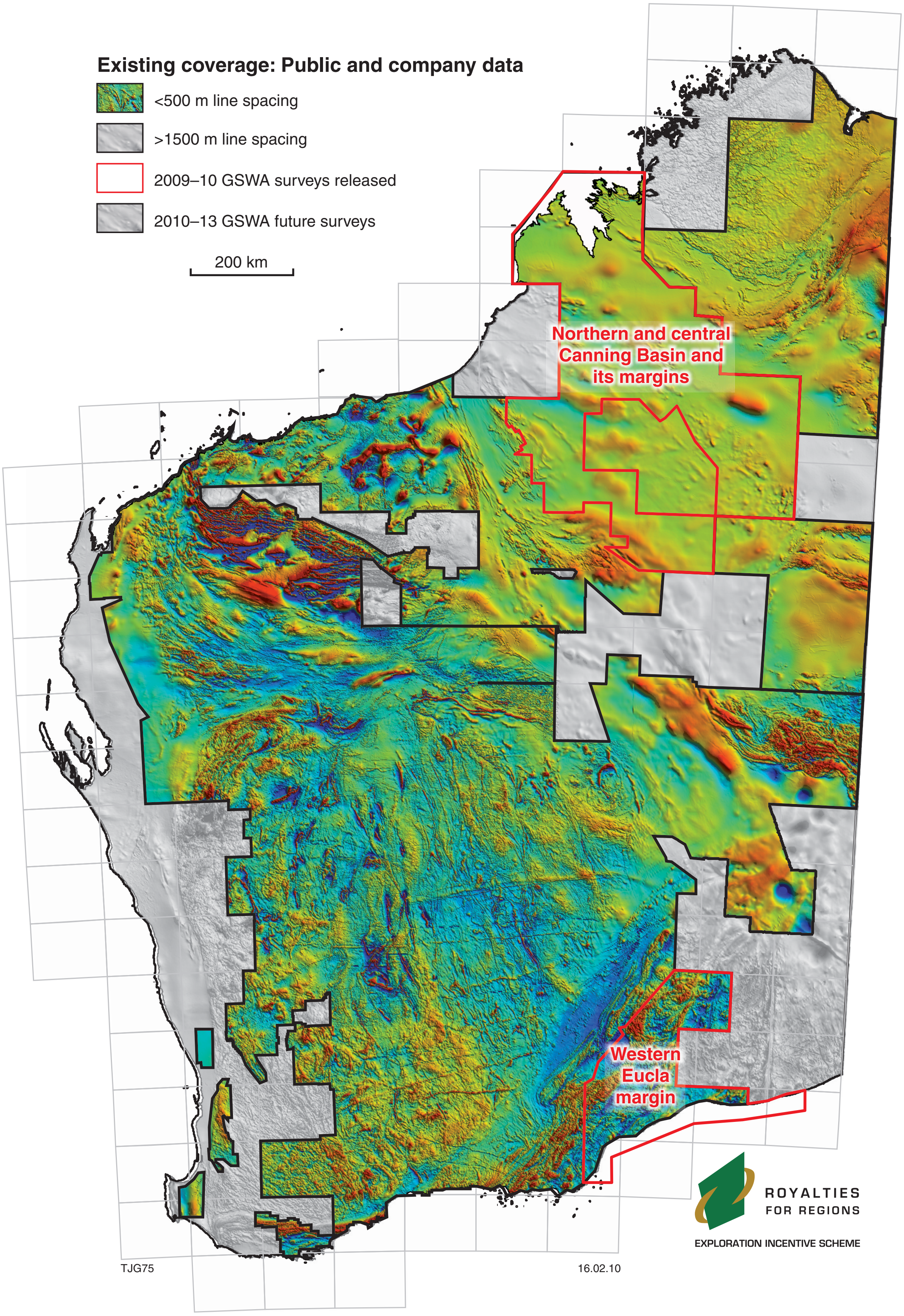

Figure 1. Aeromagnetic survey data for Western Australia. Newly released surveys are outlined in red

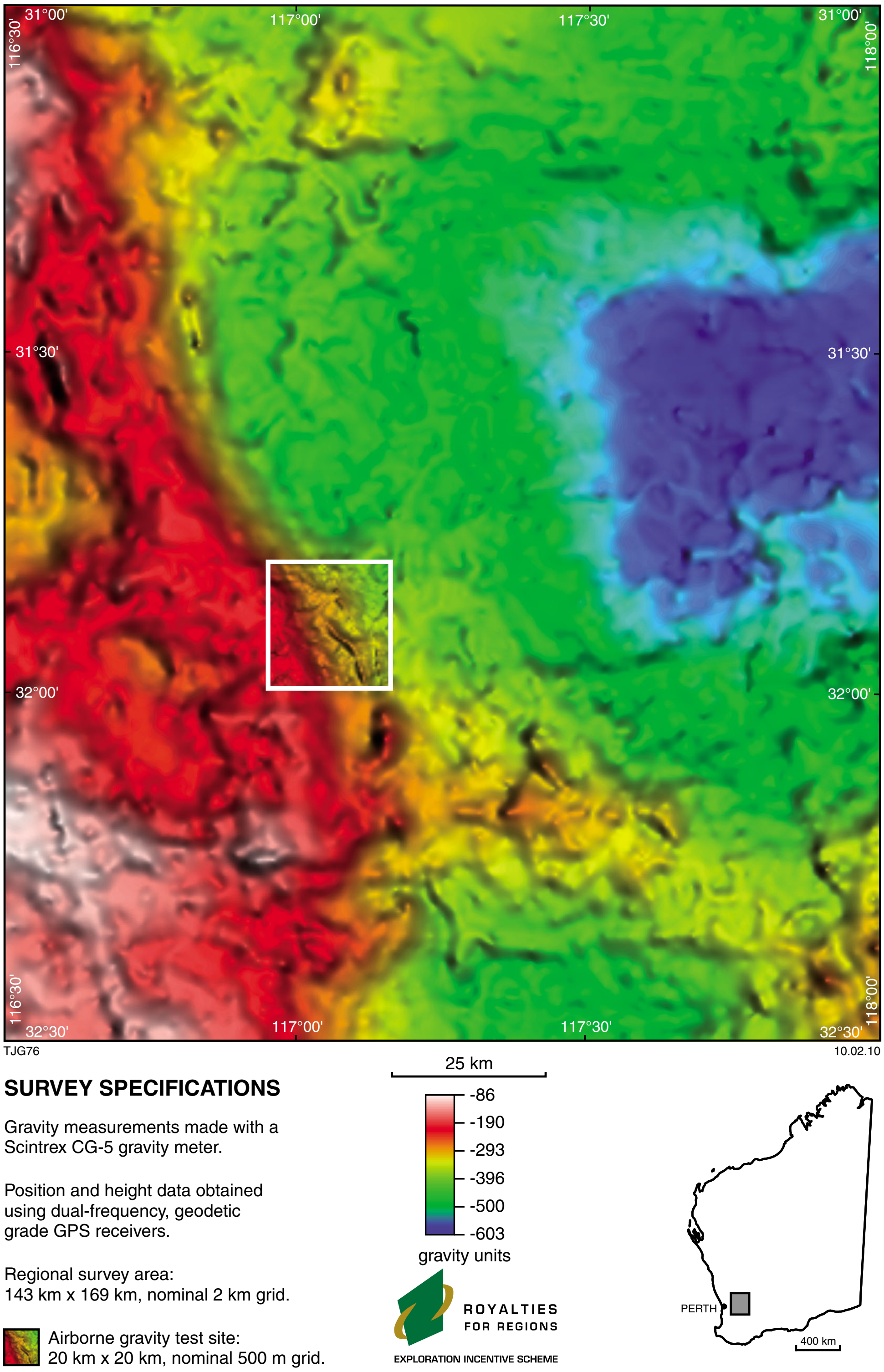

Figure 2. Cunderdin ground gravity survey, incorporating the Kauring airborne gravity test site

temperature events, including hydrothermal fluid flow and mineralization. In addition, we have expanded a program of isotopic analysis for whole rock Sm–Nd analyses, which will initially concentrate on refining the Nd isotope map of the Yilgarn Craton (Cassidy and Champion, 2007). Analysis of the Lu–Hf isotopic system in zircon previously dated using SHRIMP U–Pb geochronology is a relatively new technique that can be used as a tracer of interaction between the crust and the mantle. These techniques are important for regional-scale targeting linking large-scale mineralization to relatively juvenile magmas derived from underlying fertile, metasomatized upper mantle (Hronsky and Groves, 2009)

Within the EIS programs we are planning to modernize, expand, and integrate our systems to allow our geoscience databases to be accessed and interrogated online, and for our customers to be able to create their own, customized geoscience reports and maps. Upgrading of the petroleum and geothermal, as well as the mineral databases will streamline exploration reporting and information release. Of particular importance will be access to mineral drillhole information, and its related geochemistry. GSWA has purchased the entire TerraSearch surface and downhole geochemistry database for WA. The dataset covers large areas of the State and includes more than 1.1 million data points, most of which are multi-element geochemistry from drillholes. The exploration geochemistry data were captured from open-file company reports, and validated in terms of sample location and data quality.

There will be an expansion of cooperative projects between GSWA and other government geoscience organizations, including Geoscience Australia and CSIRO, and with university earth science departments and research centres of excellence such as the Centre for 3D Mineral Mapping (C3DMM), CET, WA Geothermal Centre of Excellence, and JdeLCMS. These projects will focus on the provision of strategically important information on mineral and petroleum systems, particularly for exploration targeting in underexplored greenfields regions, and in emerging areas such as tight gas, geothermal energy, and carbon dioxide geosequestration, where skills are in short supply. GSWA is already playing a key role in providing expert advice and assisting with the coordination of WA projects to identify the best places to sequester carbon dioxide both from coal-fired power plants and the LNG industry.

Our aim is to develop an integrated approach to the delivery of the new and expanded datasets and their interpretation — all based on development of the capability to model and visualize geological and geophysical data in 3D. Integration of the modelling of crustal architecture with geochronology, isotopic signatures, an understanding of geodynamic setting, and of the mineral systems present in an area will act as a powerful guide to exploration potential.

The challenge for GSWA, the resource exploration industry, and the research community that supports this vital sector of the Western Australian economy is to ensure that the datasets and products generated under EIS are effective in generating new exploration targets in underexplored regions, particularly under thin soil and sedimentary basin cover. The identified targets may then qualify for funding under the Government co-funded drilling scheme component of EIS. The export of WA's expertise and services to the resources sector worldwide will provide a long-term economic base for the State.

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ROYALTIES FOR REGIONS
EXPLORATION INCENTIVE SCHEME

Exploration Incentive Scheme Co-funded Exploration Drilling Program

by

M Ellis

In early April 2009 in fulfillment of an election commitment, the Western Australian government announced funding of a five-year, $80 million Exploration Incentive Scheme (EIS). The objective of EIS is to encourage exploration within Western Australia, particularly in minerals greenfields areas and frontier petroleum basins, and maintain it at the levels needed for the long-term sustainability of the State's resources sector. The scheme also provides some shorter term stimulus for the exploration industry during the exploration downturn caused by the global financial crisis. Importantly, the funding of a large exploration incentive package at this time signals that the WA Government is serious about fostering investment in the State's resources sector and is concerned about the sustainability of resource production if discovery rates are not increased.

A major component of the scheme is the Government Co-funded Exploration Drilling Program allocated $20.5 million out of EIS funding of $80 million. The aim of this program is to encourage high-quality, technically and economically sound projects that promote new exploration concepts and new exploration technologies.

Applications are called once a year for drilling projects that will take place in the following financial year. The first round of Co-funded drilling in 2009–10 was highly competitive with over 160 applications submitted requesting $15 million of co-funding. A total of 35 grants were made from the $3 million available to support projects in 2009–10. Although all the successful applicants were searching for mineral commodities the program welcomes applications from petroleum and geothermal explorers. More than $5 million will be available to fund projects to be undertaken during 2010–11.

In 2010, applications will be accepted online between 22 February 2010 and 19 March 2010 for drilling to be undertaken in 2010–11. The applications are evaluated by a team of experienced independent exploration geologists all of whom are members of one of the peak professional bodies and are bound by confidentiality agreements with the Department as well as by their own professional bodies' codes of ethics.

The applications are evaluated against a number of criteria, including potential to advance exploration activity in under-explored areas, testing areas of previous ineffective drilling and return of data in the form of core and subsequent analyses. In 2009–10, multi-phase programs where the second and subsequent phases were solely dependent on the success of the previous phase were considered for funding of the first phase only.

Feedback from industry has meant that some changes have been made to the 2010–11 program. These have been ratified by the Drilling Advisory Committee, which is made up of representatives of all the industry bodies in WA. This committee has a mandate to provide recommendations on the broad policy framework of the Co-funded drilling program as well as annually reviewing the operations of the program and recommending amendments to the guidelines.

Successful applicants can receive refunds of up to 50% of their direct drilling costs capped at $150 000 for a multi-hole project or at $200 000 for a single deep hole. This funding is paid by the Department of Mines and Petroleum (DMP) in two tranches, the first payment being made after completion of the drilling and receipt of the interim drilling report, with final payment after submission of the final report including all promised data and core.

Core collected by companies that gain Co-funding will be made available on open-file access in the relevant core library after a short six-month confidentiality period. Final reports of the drilling programs will also be released online via the WAMEX database after a similar confidentiality period.

Although multiple applications are welcome from explorers, it is recognized that some companies could gain a significant advantage by virtue of the remote location of tenement holdings and could gain multiple grants for drilling programs on contiguous or co-located tenements. Although one of the aims of the program is to encourage exploration in remote underexplored areas, it is also important to ensure a good spread of commodities and recipients. The Drilling Advisory Committee has recommended that if a company that has submitted multiple applications (regardless of location or commodity) is successful with one application, all its subsequent applications in a funding round will be burdened with a small handicap in the rating assigned to the applications. If the applications are competitive despite the handicap they will still be successful in attracting a grant.

Special provision has also been made for bona fide prospectors. A pool of funding, up to $200 000, has been allocated for distribution to applicants who submit competitive applications. Prospectors' grants will be capped at $20 000 funding per project with funding being paid similarly to the refund model of the general grant. Additionally 25% of funding of a prospector's grant will be required to be spent on analysis of samples collected from the drilling, unless the drilling is cored and the core submitted to DMP. Prospectors are not precluded from applying for funding with a higher cap under the potentially more competitive general round of applications.

Although the criteria for success in this program is activity undertaken and data submitted, there are already indications of both commercial and geological gains coming from the first round with drilling finding good gold intercepts in the west Musgrave, pointing to a new gold province in what has previously been regarded as a nickel area.

The Co-funded Drilling Program will run for the full term of EIS, with further co-funding of nearly $6 million being made available in 2011–12 and again in 2012–13. Further details can be found at: <www.dmp.wa.gov.au/eis>.

Delivering pre-competitive data for onshore energy exploration: Geoscience Australia programs in Western Australia

by

N Stolz[1]

The Onshore Energy Security Program (OESP) is a five-year scheme announced in 2006 designed to reduce risk in exploration and development of onshore energy resources in Australia. The program received $58.9 million of funding to acquire and deliver pre-competitive geophysical and geochemical data as well as value-added geological interpretations and other products for the exploration industry. Projects within the scheme were implemented either at the continental scale, or were focused on particular geological regions identified as having potential to host undiscovered energy resources. The main components of OESP are:

- An Australia-wide airborne geophysical survey (AWAGS) to improve the quality of airborne radiometric and magnetic images for uranium and geothermal energy exploration
- A national geochemical survey to provide consistent baseline information about chemical concentrations in the crust, particularly radioelements such as uranium and thorium
- Regional-scale (100 km to 1000 km) deep-crustal reflection seismic surveys targeting areas prospective for hydrocarbon, uranium, and geothermal energy resources
- Regional-scale Airborne Electromagnetic surveys targeting geological areas with potential for uranium mineralization
- A national project aimed at improving the quality of pre-competitive data and knowledge for targeting geothermal energy systems
- Regional-scale interpretations of the geodynamic framework of major energy provinces based on seismic, potential-field, and other geoscientific datasets.

A full description of OESP projects can be found on the Geoscience Australia website:

<http://www.ga.gov.u/minerals/research/oesp/index.jsp>

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Paterson Province AEM Survey, Western Australia

Regional Airborne Electromagnetic (AEM) surveys are a major component of OESP. The surveys aim to map regional-scale geological features such as unconformities and paleochannel systems that may be controlling uranium mineralization. Production of interpretation products continues apace for the Paterson Province AEM survey flown during 2007 and 2008. The drillhole database compiled to assist with interpreting the AEM data has been released to the public as a standalone product. The database includes locations for over 6500 publicly available drillholes in the Paterson region and logs for over 4300 of these holes (Fig. 1).

Sample-by-sample layered earth inversion (LEI) results including geo-located conductivity–depth sections and depth-slice grids will be released in March 2010. An example of an interpreted LEI conductivity–depth section is shown in Figure 2. The results will be summarized in a report that includes a selection of data products, a reference model description, and validation of the inversions using public-domain drillhole logs. Another important product is the percent data influence (PDI), which indicates the boundary between the data-driven and the model-driven results of the inversion. Since the PDI indicates the effective depth penetration of AEM, Geoscience Australia (GA) has used this parameter to create an AEM 'Go-map' showing where AEM is expected to map beneath surface materials.

The AEM project team will present key results from the Paterson AEM survey to industry and other stakeholders at a one-day workshop in Perth planned for April 2010. In August GA will release an interpretation report describing the geological and energy implications of the AEM survey. The report will highlight the use of regional-scale AEM surveys for decreasing exploration risk in frontier exploration areas for a variety of commodities, particularly uranium.

Kidson–Paterson seismic line

The Canning Basin represents a vast geological frontier in northwestern Australia. The Kidson Sub-basin is a southern

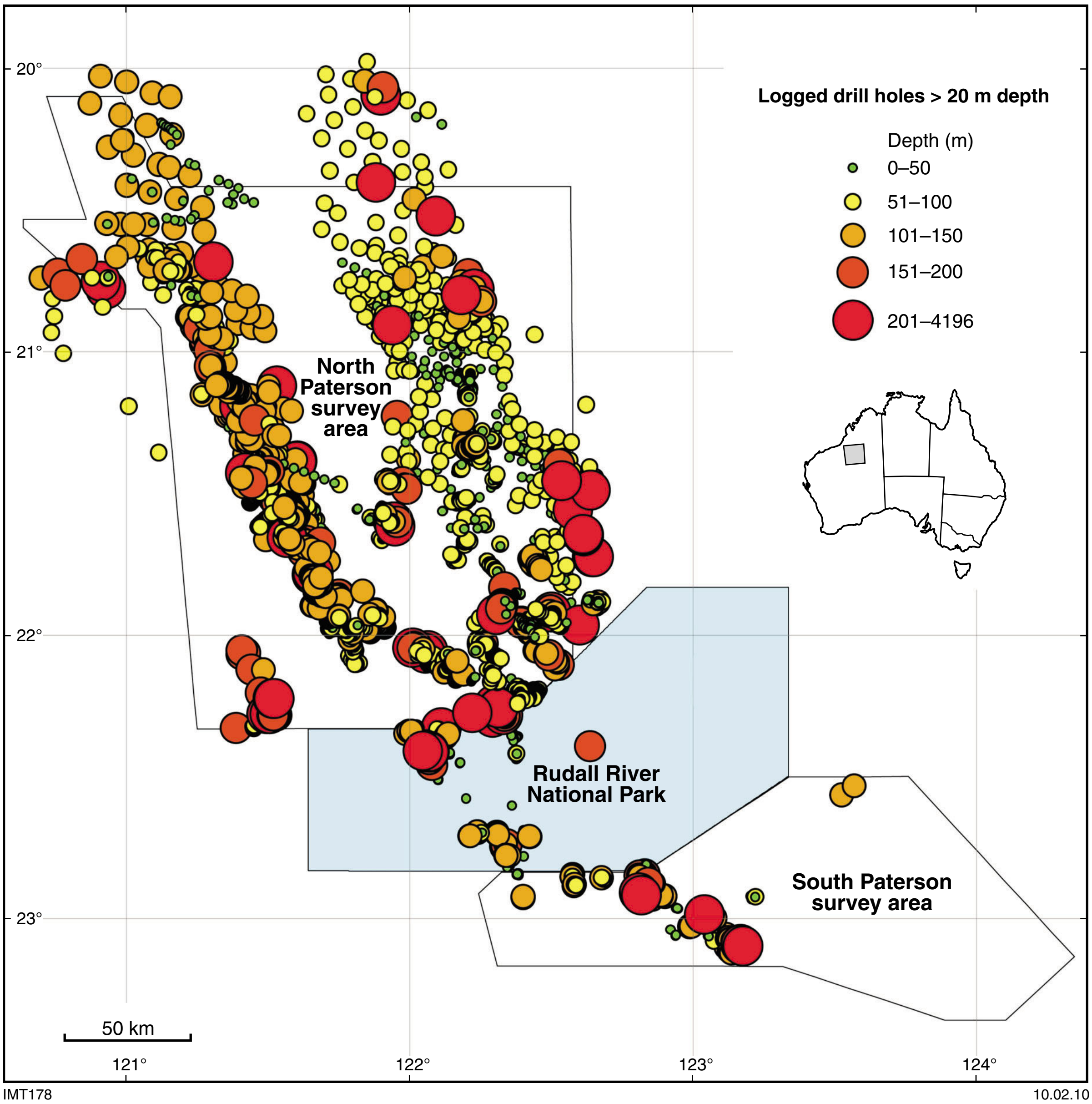

Figure 1. Location and depth of drillholes included in the recently released database, shown with the survey boundaries of the Paterson AEM Project. Inset map shows the location of the Paterson region in northwest Western Australia.

depocentre of the onshore Canning Basin, and is known to contain up to 7 km of Early Ordovician to Cretaceous sedimentary rocks, representing the most complete stratigraphy in the region. Very little data from previous exploration efforts are available and they are of old vintage.

Given that a thick sequence of Ordovician sedimentary rocks is likely to include mature source rocks, the Kidson Sub-Basin may represent a major hydrocarbon province analogous to those encountered in China's Tarim Basin. For this reason, the sub-basin is being targeted in a major deep reflection seismic acquisition project in 2010. This will be the last seismic line to be completed by GA under OESP.

Funding for the project has been secured, and includes a significant contribution from GSWA under their Exploration Incentive Scheme (EIS). A transect of over 750 km along the Canning Stock Route is proposed (Fig. 3), extending from the Crossland Platform in the northeast to the Paterson Province in the southwest. Negotiation by GA and GSWA staff in late 2009 has ensured cooperation from the traditional owners for this vast region.

The Kidson–Paterson seismic line will be one of the logistically most difficult projects ever undertaken by GA. The region is extremely remote with poor roads and sparse infrastructure. The Canning Stock Route is very narrow and crosses a number of sand dunes, which present a challenge to moving seismic equipment and vibroseis trucks. Accommodation and messing for the acquisition crew will also be difficult due to lack of water and suitable camp-sites.

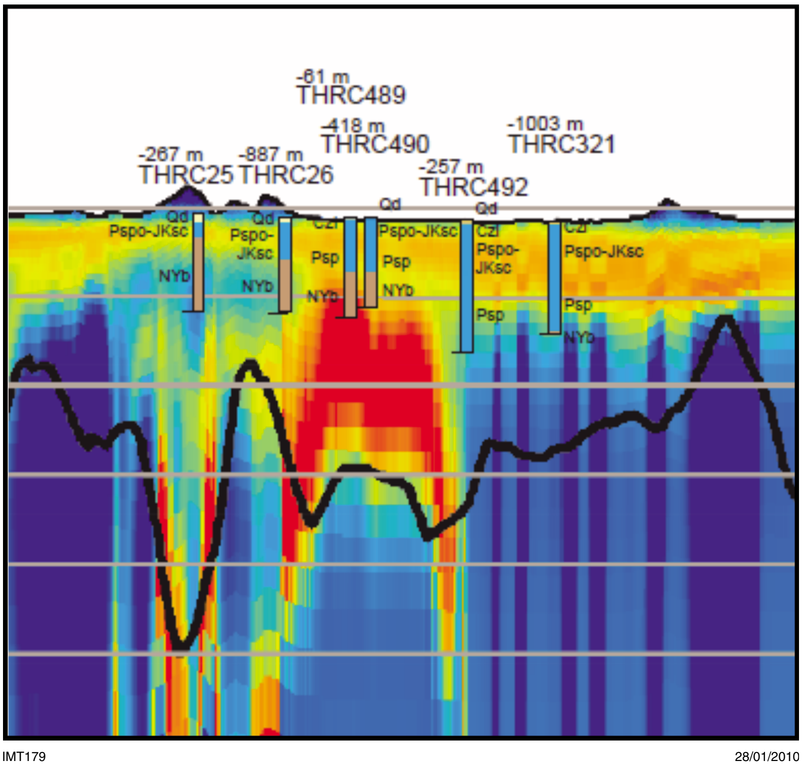

Figure 2. Drillholes with logged geology overlain on a conductivity–depth section derived from a layered earth inversion of AEM data from the Paterson Project. Hot colours indicate conductors whereas cool colours indicate resistors. The orange near-surface material corresponds to Permian (or Jurassic) sedimentary rocks and the red zone at depth corresponds to Broadhurst Shale of the Yeneena Basin. The thick black line indicates the percent data influence (PDI), or the depth to which the AEM system is effectively penetrating.

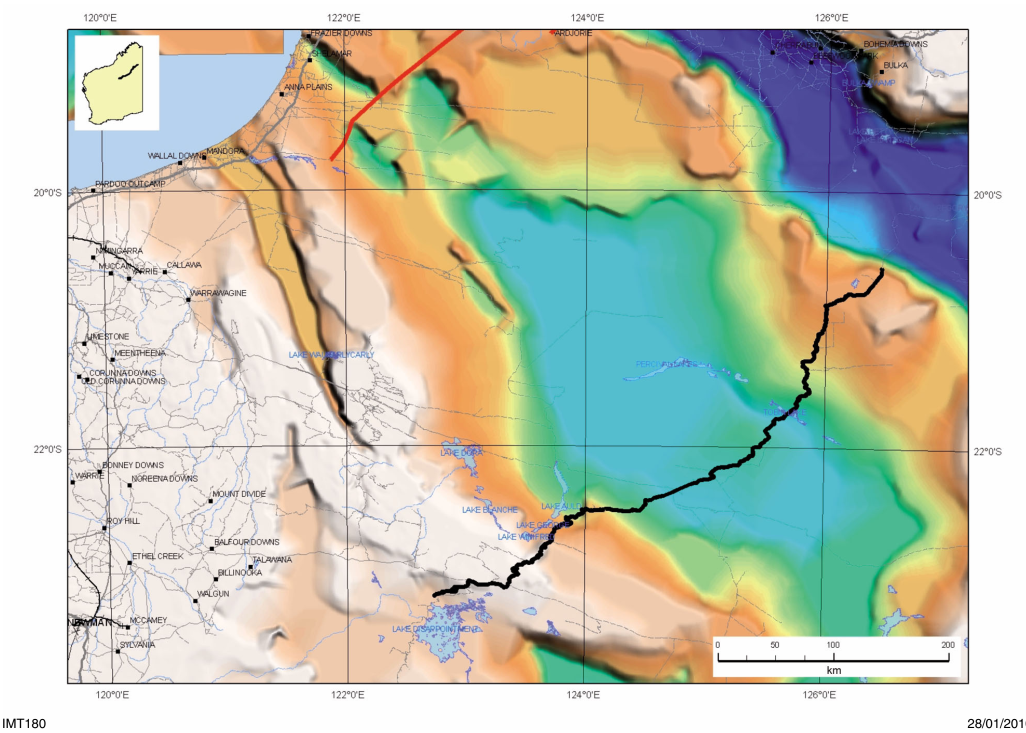

Figure 3. SEEBASE™ depth to basement image (hot colours = shallow, cool colours = deep) of the Canning Basin region in northwest WA showing the planned location of the Kidson–Paterson seismic line. Length of the proposed line shown is 776 km.

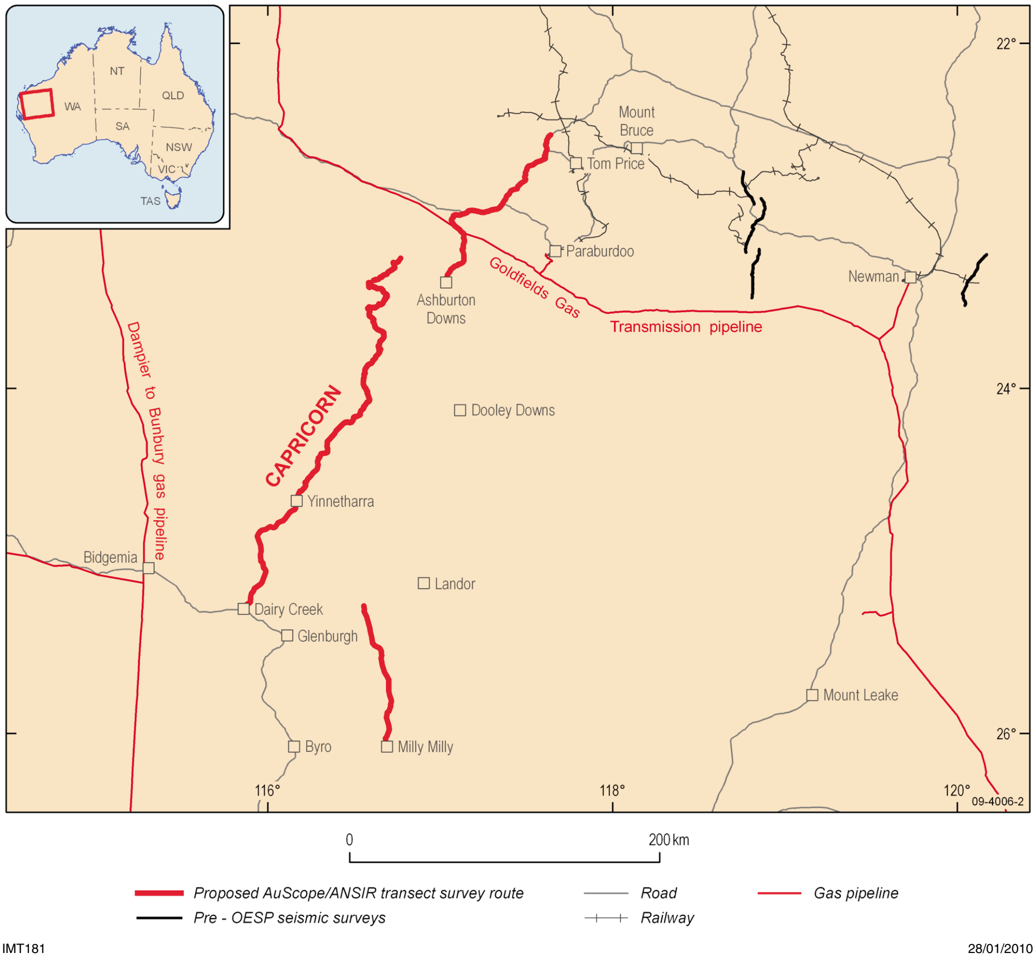

Figure 4. Location plan for the proposed Capricorn seismic line. The total length for the three line segments is about 570 km.

Seismic data acquisition is planned to commence in May. The survey is expected to take four months to complete, and will be the most expensive onshore seismic project GA has ever undertaken.

Capricorn seismic line

Other onshore seismic acquisitions being managed by Geoscience Australia in 2010 include the AuScope–GSWA-funded line in the Capricorn region and a GSWA-funded line in the northern Yilgarn. AuScope Earth Imaging is funded by the National Collaborative Research Infrastructure Strategy (NCRIS) to acquire deep crustal reflection seismic, passive seismic, and magnetotelluric data across interpreted major tectonic structures in the Australian continent. The Capricorn seismic traverse seeks to establish whether the Archean Pilbara and Yilgarn Cratons are directly linked beneath the Capricorn Orogen, or if they are separated by Proterozoic crust. It will also image the basement beneath the Proterozoic basins in the area such as the Ashburton and Earaheedy Basins. The location of the proposed transect is shown in Figure 4. Acquisition is expected to commence around June–July 2010.

Conclusion

OESP has been underway for three years and has successfully released a number of datasets that demonstrate the relevance of its programs to the resource exploration sector. National and regional projects are now well-established and occupied in processing, analysing, and reporting on acquired data to enhance the impact of the program. Datasets and products are focused on hydrocarbon, geothermal, and uranium energy systems, but will also assist companies exploring for base metals, gold, and other commodities, and can also be applied to land use management and groundwater assessments.

Geology and physical volcanology of the Bentley Supergroup, Musgrave Province

by

M Werner and HM Howard

The Bentley Supergroup is well-exposed in the west Musgrave Province of central Australia and consists of supracrustal volcano-sedimentary rocks of latest Mesoproterozoic age, with U–Pb geochronology indicating deposition between about 1080 and 1025 Ma (Smithies et al., 2008). This depositional age range brackets the age of emplacement of the mafic–ultramafic Giles intrusions, which form part of the Warakurna large igneous province (Wingate et al., 2004), a magmatic expression of the Giles Event (Evins et al., in press).

The Bentley Supergroup is primarily composed of bimodal volcanogenic rocks comprising voluminous and widespread extrusive felsic and mafic igneous rocks such as rhyolitic to dacitic lava flows and ignimbrite sheets, as well as basaltic to andesitic lavas and mafic volcaniclastic rocks. Interlayered with the volcanogenic rocks are continental siliciclastic and minor lacustrine calcareous rocks (Daniels, 1974). The extrusive igneous rocks of the Bentley Supergroup are also part — together with coeval intrusive igneous rocks — of the Warakurna Supersuite (Howard et al., 2007).

Outcrops of the Bentley Supergroup are confined to the west Musgrave Province, where they unconformably overlie older Mesoproterozoic metamorphic basement (Daniels, 1974). The supergroup was deposited within an extensive, probably intracontinental, rift basin much larger than its present outcrop extent. In the Blackstone area, the Bentley Supergroup is represented by the Kunmarnara and Tollu Groups, consisting of a succession of coarse siliciclastic rocks and amygdaloidal basalts unconformably overlain by felsic and then basic to intermediate lavas, and the Skirmish Hill Volcanics (Smithies et al., 2008). In the Warburton–Jameson area, Daniels (1974) suggested the existence of three structural domains separated by inferred caldera faults. The southwestern part of the west Musgrave Province is characterized by the south-dipping and -younging volcano-sedimentary Pussy Cat, Cassidy, and Mission Groups (Fig. 1). This succession has a cumulative thickness of several kilometres and forms an arcuate, southeast- to east-trending belt. The southern margin of this succession is unconformably overlain by the Townsend Quartzite, the basal unit of the Officer Basin succession. To the north and east lie the Scamp and Palgrave areas, which were originally interpreted by Daniels (1974) as volcanogenic caldera subsidence areas.

Recent field mapping has focused on the northern half of the MOUNT EVELINE* 1:100 000 map sheet (Fig. 1). In this area, the Pussy Cat Group is represented by the Glyde Formation and the intercalated Kathleen Ignimbrite. The lower Glyde Formation is dominated by dark-coloured, mafic volcaniclastic sedimentary rocks, and the upper part is dominated by amygdaloidal mafic lavas. The lower volcaniclastic rocks comprise mainly laminated to massive mudstones, plane-bedded and trough cross-bedded arkosic sandstones, and poorly sorted, matrix-supported mud- and debris-flow deposits (lahars; Fig. 2a). Some finely laminated mudstones may represent subaqueous ash-fall tuffs. Minor components — important for paleoenvironmental reconstruction — include evaporitic horizons and stromatolites. The Glyde Formation was deposited in a volcanically active fluvio-lacustrine environment with mafic volcanic source components commonly dominating over felsic components in the volcaniclastic deposits. Moderate-temperature, low-pressure regional metamorphism overprinted Glyde Formation volcaniclastic rocks to biotite- and epidote-rich, commonly hornblende-porphyroblastic hornfels and micro-granofels, whereas mafic volcanic rocks were transformed into epidotitic amphibolites.

The Kathleen Ignimbrite has a maximum thickness of over 500 m and forms a mappable unit within the Glyde Formation. It is mainly composed of rhyolitic flow-banded lava-like deposits, which Daniels (1974) interpreted as densely welded and rheomorphic pyroclastic rocks. Observations supporting a pyroclastic origin include the irregular and patchy distribution of quartz and feldspar phenocrysts and crystal fragments, the presence of cognate rhyolite-porphyry and mafic-volcanic pyroclasts, alternating felsic and mafic layers in its basal part, relicts of glass shards (Fig. 2b) and pumice breccias in its higher part, and fiamme textures and stratified crystal-tuffs near the top. The Kathleen Ignimbrite also contains upwardly intruded clastic dykes of Glyde Formation material, indicating that the ignimbrite was deposited rapidly onto semi-consolidated, water-bearing volcaniclastic sediments.

* Capitalized names refer to standard 1:100 000 map sheets.

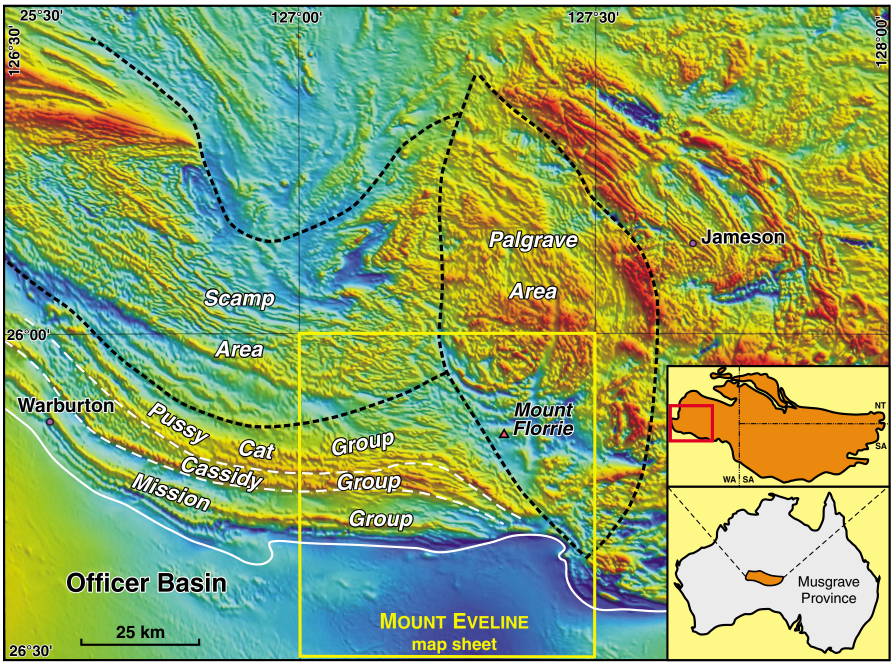

Figure 1. Aeromagnetic image showing the area in which the Bentley Supergroup is exposed in the Warburton–Jameson area of the west Musgrave Province. The dashed black lines mark the approximate positions of caldera faults and structural domains as postulated by Daniels (1974). However, the aeromagnetic data as well as our own lithological and structural observations cannot be fully reconciled with Daniels' interpretation. The red frame in the upper inset indicates the position of the area shown in the aeromagnetic image.

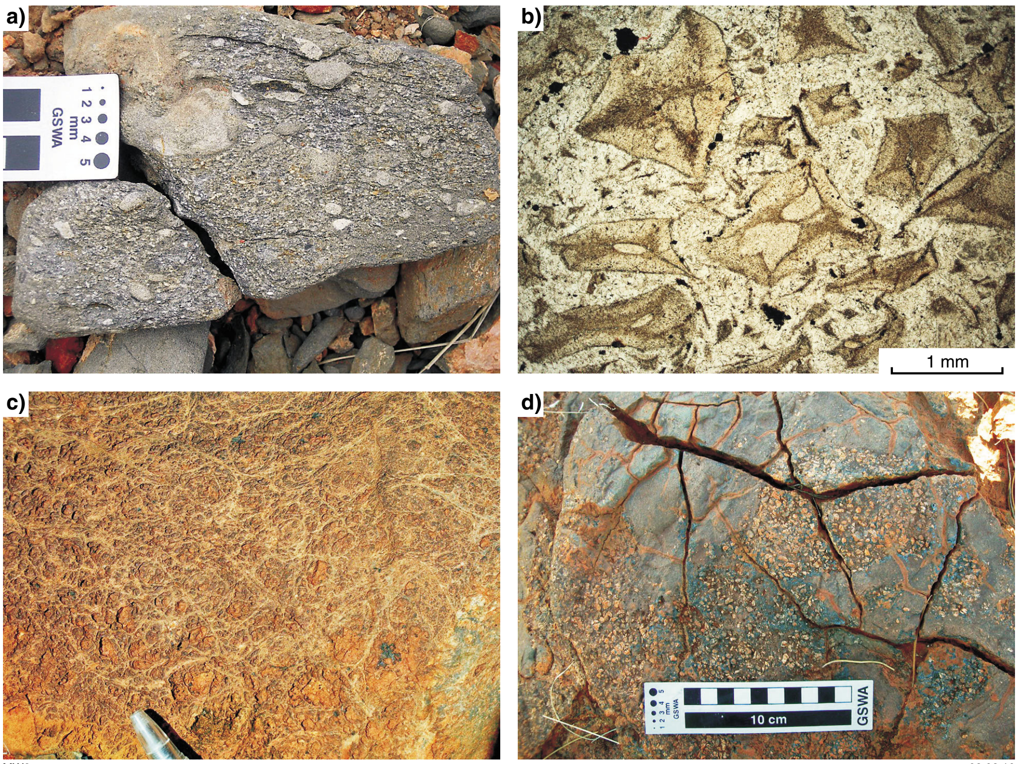

Figure 2. (a) Coarse-grained mafic volcaniclastic rocks of the Glyde Formation; (b) relict glass shards in the upper part of the Kathleen Ignimbrite (photomicrograph in plane-polarized light); (c) relict perlitic cracks in formerly glassy felsic volcanic rock of the Palgrave area; (d) intrusive phenocryst-rich rhyolite porphyry forming peperites within fine-grained, semi-consolidated volcaniclastic rocks of the Glyde Formation.

The Scamp area lies north of the Pussy Cat Group outcrop belt. Daniels (1974) inferred that a major east-trending caldera fault separates the two areas. Our recent mapping of the southeastern Scamp area instead indicates that the Scamp volcanics and the Pussy Cat Group are part of the same south-dipping succession, with the Scamp volcanics representing a deeper stratigraphic level. The Scamp area north of the Kathleen Ignimbrite is dominated by extrusive rhyolitic volcanic rocks, including both lava flows and ignimbrites. In its eastern part, mafic volcanic and volcaniclastic rocks form significant intercalations in the rhyolitic portions and are strikingly similar to Glyde Formation rocks.

The Palgrave area, a northerly trending oval area of outcrop, was again interpreted by Daniels (1974) as a caldera. However, our lithological and structural data do not support this interpretation. The succession comprises roughly north-trending, west-dipping and -younging felsic volcanic and pyroclastic rocks with minor mafic volcaniclastic intercalations. Formerly vitric volcanic rocks are typically strongly spherulitic or perlitic (Fig. 2c). These rocks are similar to those of the Bentley Supergroup further west, although here they represent a more proximal lithofacies. The Palgrave succession partially wraps around a large synvolcanic dome (Winburn Granite). Brittle deformation and hydrothermal alteration associated with doming and formation of a large west-northwesterly plunging fold is conspicuous in the Mount Florrie region (Fig. 1), which has recently been the site of a significant gold discovery (Handpump prospect; Beadell Resources, 2009).

On MOUNT EVELINE the intrusion of synvolcanic felsic magmas — like those of the Winburn Suite — into the Bentley Supergroup was very common. Typical rocks are rhyolite porphyries and microgranites, which form sills up to 250 m thick, dykes up to 150 m wide, and stocks such as the 4 × 6 km Mount Eveline intrusion. Some of these magmas mixed and mingled with unconsolidated or semiconsolidated volcaniclastic sediments and pyroclastics to form peperites (Fig. 2d). In the central Palgrave area, a large-wavelength magnetic and gravity anomaly suggests the presence of a large mafic intrusive body (probably Giles Suite) at depth.

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Reassessment of the geology and exploration potential of the Western Australian Amadeus Basin

by
PW Haines, HJ Allen, and K Grey

The Amadeus Basin, a relic of the Centralian Superbasin (Walter et al., 1995), is exposed over about 170 000 km^2 in central Australia. The majority lies in the Northern Territory, but about 30 000 km^2 is exposed in eastern Western Australia, with more beneath the Canning Basin to the west. The basin contains a thick Neoproterozoic to Paleozoic succession, although confirmed Paleozoic strata are limited in WA, and underwent regional folding during the Petermann (Ediacaran–Cambrian) and Alice Springs (mid Paleozoic) Orogenies. The NT portion is well known and moderately explored, but remoteness, difficult access, and poor exposure have conspired to see very little activity in the western Amadeus Basin since first-pass reconnaissance mapping by the Bureau of Mineral Resources in the early 1960s (Wells et al., 1961, 1964).

Apart from the Heavitree Quartzite and its correlative the Dean Quartzite, and the overlying Bitter Springs Formation, separate stratigraphic schemes were devised for eastern and western portions of the basin (Wells et al., 1970). Recent fieldwork by the Geological Survey of Western Australia indicates that the western Amadeus Basin shows much closer similarity to the well-established stratigraphy within the NT than previously reported and reveals new insights into the geological history of the area, necessitating a revision of basin-wide correlations (Fig. 1). Ultimately, the western Amadeus Basin should provide an important link between the Officer and eastern Amadeus Basins.

The key has been understanding the stratigraphic complexity of the poorly exposed Boord Formation and its relationship to the Carnegie Formation. These units disconformably overlie the Bitter Springs Formation in the north and south of the area, respectively, and were regarded as lateral equivalents. The Boord Formation includes glacigene strata and was previously correlated with either the Areyonga Formation (Wells et al., 1970; Weste, 1989) or Olympic Formation/Pioneer Sandstone (Grey, 1990), the glacigene units of the eastern Amadeus succession, and correlatives of the Sturt or Elatina glaciations of the Adelaide Rift Complex, respectively. Our fieldwork indicates that the Boord Formation contains not one, but two glacial units, several disconformities, and significant pre- and post-glacial intervals. In total it contains likely correlatives of the 'Finke beds' (an informal unit recognized in several petroleum wells in the NT: Grey et al., in press) and Areyonga, Aralka, Olympic, Pertatataka, and Julie Formations of the northeastern Amadeus Basin. We propose eventual abandonment of the 'Boord Formation' as presently defined, but until a new stratigraphy is finalized we use this name informally for the composite package. The new correlations are based on lithostratigraphy with strong support from stromatolite biostratigraphy. Unique stromatolite assemblages can be used to subdivide the Bitter Springs Formation into Gillen and Loves Creek Members, as in the NT, and to link the inferred correlatives of the 'Finke beds', upper Aralka, and Julie Formations to their counterparts in the eastern Amadeus and other basins throughout Australia.

The Carnegie Formation is a thick, immature siliciclastic unit, strongly resembling the lower part of the Ediacaran–Cambrian Arumbera Sandstone in the NT. Both formations contain *Arumberia*, a problematic biogenic structure first described from the Arumbera Sandstone (Glaessner and Walter, 1975). Although there is minor interfingering at the Boord–Carnegie Formation contact, we consider the latter to be mostly younger than the 'Boord Formation'. In the south, the Carnegie Formation overlies the Bitter Springs Formation with an angular unconformity, the intervening succession having been presumably uplifted and eroded in that area. Together, the Carnegie Formation and overlying Sir Frederick Conglomerate, Ellis Sandstone, and Maurice Formation are interpreted as a synorogenic package related to the Petermann Orogeny. The Sir Frederick Conglomerate is thus a likely correlative of the Mount Currie Conglomerate at Kata Tjuta (Mount Olga) in the NT. The synorogenic package probably extends across the Proterozic–Phanerozoic boundary, into the Cambrian, although the position of the boundary is unknown.

Fault-bound outliers of Amadeus Basin lie within Arunta Province basement to the north of the main basin. In addition to recognized Neoproterozoic units, the outliers contain a thick, immature, conglomeratic siliciclastic package referred to as the 'Angas Hills Beds'. Previous workers have suggested that this unit may correlate with the Devonian synorogenic (Alice Springs Orogeny) Pertnjara Group of the eastern Amadeus Basin (Blake, 1977), or be of Permian age. Although its age remains unknown, we note the similarity of clast assemblages and paleocurrent directions to the older Petermann synorogenic package in the south. Future detrital zircon dating should provide better age constraints.

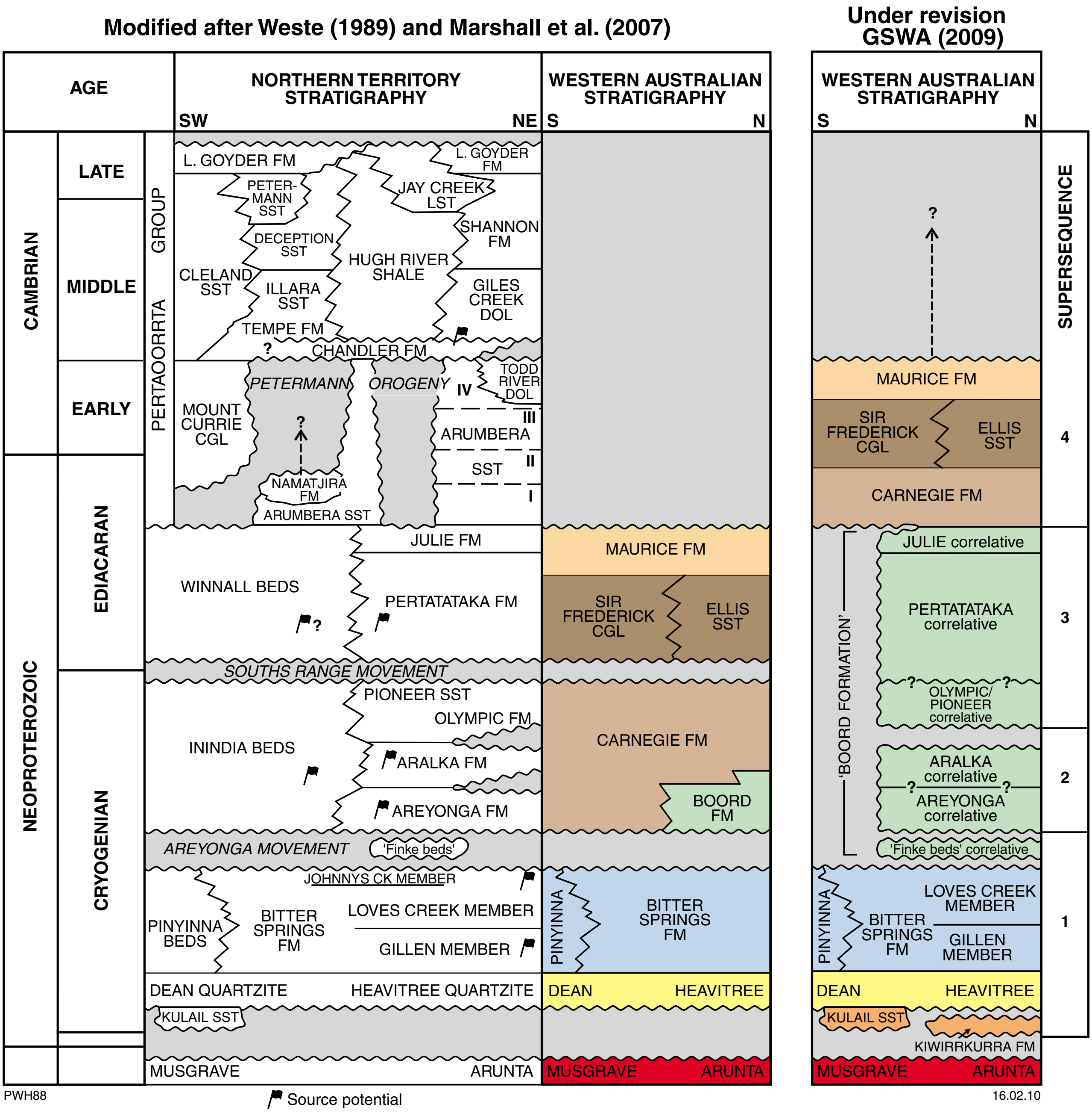

Figure 1 Neoproterozoic to Cambrian stratigraphy of the NT and WA Amadeus Basin, comparing the most commonly used current scheme on left with our revisions in progress at right. The supersequence scheme of Walter et al. (1995) is shown at far right. The Kiwirrkurra Formation and Kulail Sandstone are local units, of uncertain age, pre-dating the regional basal siliciclastic unit of the Amadeus Basin.

Thin outcrops of glacigene rocks lie unconformably on Amadeus Basin strata of various ages and basement rocks across the area. Most have previously been assigned to the Buck Formation, of assumed Permian age (Wells et al., 1964), and thus considered outliers of the Canning Basin. We located similar strata around, and north of, the Pollock Hills that had not previously been differentiated from Neoproterozoic units, or had been mapped as Mesozoic (Blake, 1977). In this area, stratigraphic relationships suggest, but do not prove, that these glacigene rocks are of Neoproterozoic age. This raises the issue of distinguishing Neoproterozoic from Permian glacial units in isolated areas lacking unambiguous stratigraphic constraints. A glacial pavement between Buck Formation and Heavitree Quartzite reported by Wells et al. (1961, 1964) was relocated during 2009 fieldwork (Zone 52, MGA 478760E 7443446N). The actual outcrop figured by Wells et al. (1961) is devoid of convincing glacial striae, but we found striae and chattermarks on polished surfaces of Heavitree Quartzite nearby, giving an unequivocal ice movement direction to the west (average vector 273°). This contrasts with the more northerly trend of ice movement reported from Permian pavements elsewhere in WA (Playford et al., 2009).

There are producing oil and gasfields in the NT in the Paleozoic section, and the Neoproterozoic succession is associated with demonstrated or possible source rocks at numerous levels (e.g. Bitter Springs, Areyonga, Aralka, and Pertatataka Formations and lateral correlatives; Marshall, 2003, 2005; Marshall et al., 2007; Fig. 1), numerous shows, and the sub-economic Dingo gasfield. Exploration for Neoproterozoic plays is ongoing. The western end of the basin may also be prospective for hydrocarbons and uranium. Actual source potential or maturity cannot be determined from weathered surface outcrops, but the recognition of correlatives with similar facies to units with source potential in the NT, raises the potential for petroleum in western parts of the basin, or in the overlying Canning Basin where they are juxtaposed with source and fluid pathways of the Amadeus succession. There is also strong evidence for halotectonics, both from geophysics (Dentith and Cowan, 2009) and surface outcrop expression. This is likely related to a salt unit within the upper Gillen Member, which is widespread in the east, and hence a salt seal is expected over the 'Gillen petroleum system' at depth within WA.

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Building the Proterozoic Albany–Fraser Orogen on the Yilgarn Craton margin: setting the scene for Tropicana

by

CV Spaggiari, CL Kirkland, MJ Pawley, MTD Wingate, RH Smithies, and HM Howard

The Yilgarn Craton is truncated by Proterozoic orogens on all sides, with little or no indication of its former extent. Its southern and southeastern margins are cut by the Albany–Fraser Orogen, which is divided into the Northern Foreland (representing reworked Yilgarn Craton) and the Paleo- to Mesoproterozoic Kepa Kurl Booya Province (representing the pre-amalgamation basement components). The Kepa Kurl Booya Province is divided into the Biranup, Fraser, and Nornalup Zones, respectively, from northwest to southeast (Fig. 1; Spaggiari et al., 2009). These are intruded by Mesoproterozoic granitic rocks of the Recherche and Esperance Supersuites, and overlain by various cover rocks. High-temperature metamorphism and deformation have affected the majority of the orogen, making it difficult to distinguish reworked Archean Yilgarn Craton rocks from orogenic Proterozoic rocks without the aid of geochronology. Such a distinction is fundamental to understanding the tectonic evolution of both the craton margin and the orogen, and consequently the formation of gold deposits such as Tropicana, and other gold deposits within the orogen (Fig. 1). The most popular exploration model for Tropicana is that of reworked Archean gold, yet there are no published data to support such a model. It is also not clear whether this model is applicable on a regional scale, away from the Tropicana–Havana area.

Biranup Zone

Geophysical imagery and geochronology* indicate that the dominantly 1690 to 1660 Ma Biranup Zone wraps the entire exposed length of the southern and southeastern Yilgarn Craton over a distance of at least 1200 km, and is the principal unit adjoining the craton (Fig. 1). In the eastern Biranup Zone, granitic rocks dated between 1690 and 1680 Ma intruded psammitic to semipelitic metasedimentary rocks very shortly after their deposition (Fig. 2). Dating of folded leucosomes and cross-cutting pegmatites indicates that folding and migmatization of both the metasedimentary and granitic rocks occurred at c. 1680 Ma. This deformation event was followed by the intrusion of a suite of granitic to gabbroic rocks and their hybrids, dated at c. 1665 Ma.

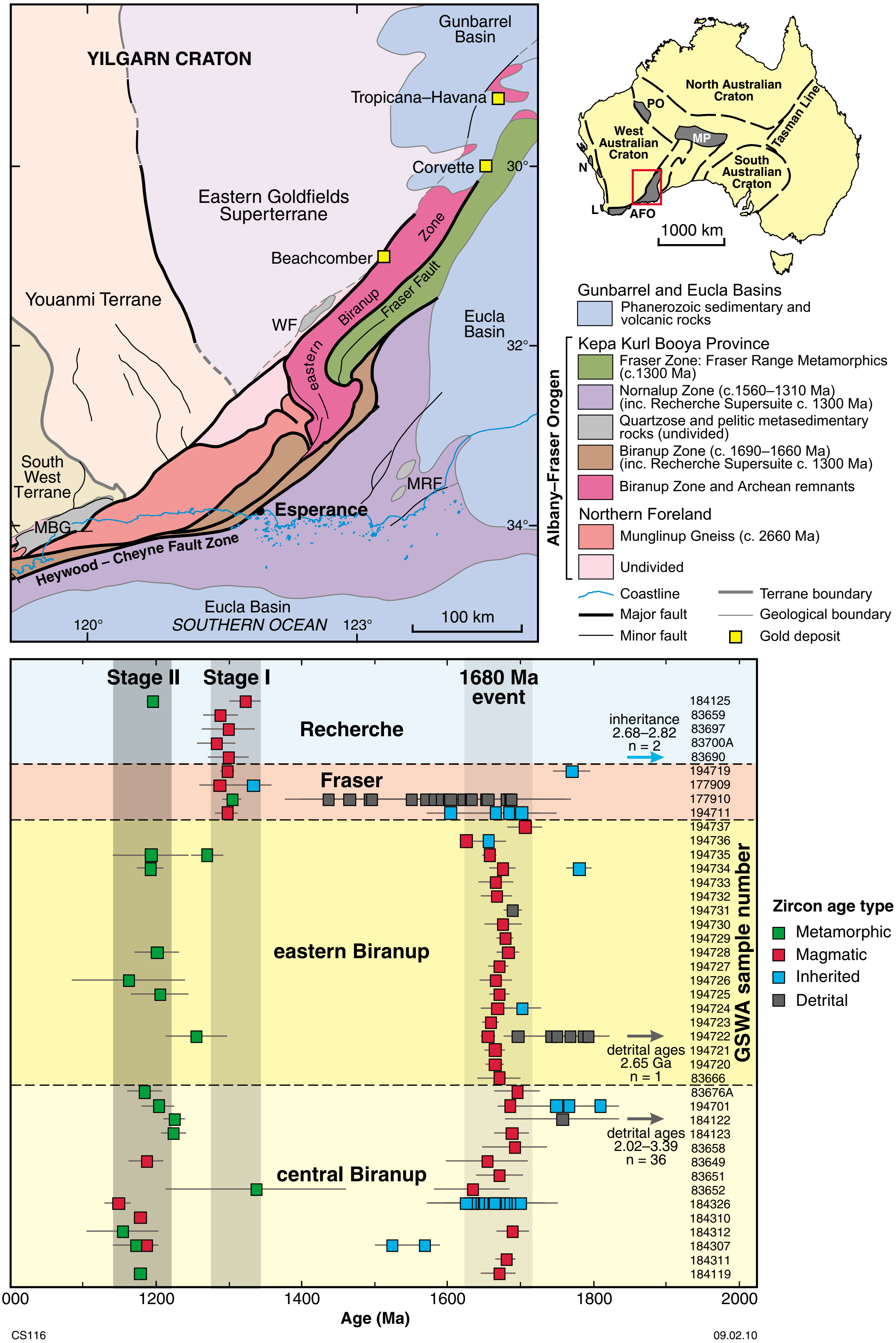
The sequence of events indicates rapidly evolving crust within a dynamic tectonic environment between 1690 and 1660 Ma. However, it is not clear whether the Biranup Zone formed directly on the Yilgarn Craton margin, perhaps as a continental arc, or whether it is an exotic terrane that was subsequently accreted onto the Yilgarn Craton margin. From more than 30 samples dated so far, virtually no Archean zircon inheritance has been recorded (Fig. 2), which favours the latter interpretation, as does the alkaline composition of rapakivi-textured metagranitic rocks. There is also no direct evidence of a tectonothermal event at this time in the southeastern Yilgarn Craton.

The Biranup Zone was extensively reworked at high temperatures along its entire length mainly between 1200 and 1180 Ma (equivalent to the c. 1215–1140 Ma Stage II of Clark et al., 2000; Fig. 2). Interestingly, there is no conclusive evidence of Stage I (c. 1345–1280 Ma), which is recorded prominently in the adjoining Fraser Zone to the southeast. The oldest metamorphic age in the Biranup Zone, at c. 1270 Ma, is about 10 Ma younger than granitic magmatism in the Fraser Zone (Kirkland et al., 2010). However, a common connection between the eastern Biranup and Fraser Zones is indicated by a record of uplift and cooling between Stages I and II.

Figure 1. Preliminary geological sketch map of the eastern Albany–Fraser Orogen and east Yilgarn Craton (adapted from Spaggiari et al., 2009) showing locations of the main gold prospects and deposits. MBG = Mount Barren Group; MRF = Mount Ragged Formation; WF = Woodline Formation. Inset map shows the location of Mesoproterozoic tectonic units of Australia; MP = Musgrave Province; PO = Paterson Orogen; N = Northampton Complex; L = Leeuwin Complex; AFO = Albany–Fraser Orogen.

Figure 2. Time–space diagram for the Albany–Fraser Orogen. The diagram includes all ion microprobe (SHRIMP) U–Pb zircon and baddeleyite ages determined by the Geological Survey of Western Australia within the region. Within each major lithostratigraphic domain (Recherche Supersuite, Fraser Zone, eastern and central Biranup Zone) the data are arranged in geographic order from southwest at the base to northeast at the top, and show no apparent trends. Note that sample 194722 is a mylonitized, pegmatite-bearing metasedimentary rock, and hence contains both magmatic and detrital components. n = number of zircons.

* Individual geochronology records for each sample will be available online at <http://www.dmp.wa.gov.au/geochron>


YILGARN CRATON
Gunbarrel Basin
Tropicana–Havana
Corvette
30°
Eastern Goldfields Superterrane
Beachcomber
Youanmi Terrane
WF
eastern Biranup Zone
Fraser Fault
Eucla Basin
32°
South West Terrane
MRF
MBG
Esperance
34°
Heywood – Cheyne Fault Zone
Eucla Basin
SOUTHERN OCEAN
120°
123°
100 km
North Australian Craton
PO
West Australian Craton
MP
Tasman Line
South Australian Craton
N
L
AFO
1000 km
Gunbarrel and Eucla Basins
Phanerozoic sedimentary and volcanic rocks
Albany–Fraser Orogen
Kepa Kurl Booya Province
Fraser Zone: Fraser Range Metamorphics (c.1300 Ma)
Nornalup Zone (c.1560–1310 Ma) (inc. Recherche Supersuite c. 1300 Ma)
Quartzose and pelitic metasedimentary rocks (undivided)
Biranup Zone (c. 1690–1660 Ma) (inc. Recherche Supersuite c. 1300 Ma)
Biranup Zone and Archean remnants
Northern Foreland
Munglinup Gneiss (c. 2660 Ma)
Undivided
Coastline
Major fault
Minor fault
Terrane boundary
Geological boundary
Gold deposit
Stage II
Stage I
1680 Ma event
Recherche
inheritance 2.68–2.82 n = 2
Fraser
eastern Biranup
detrital ages 2.65 Ga n = 1
central Biranup
detrital ages 2.02–3.39 n = 36
184125
83659
83697
83700A
83690
194719
177909
177910
194711
194737
194736
194735
194734
194733
194732
194731
194730
194729
194728
194727
194726
194725
194724
194723
194722
194721
194720
83666
83676A
194701
184122
184123
83658
83649
83651
83652
184326
184310
184312
184307
184311
184119
GSWA sample number
Zircon age type
Metamorphic
Magmatic
Inherited
Detrital
1000
1200
1400
1600
1800
2000
Age (Ma)
CS116
09.02.10

Fraser Zone

The c. 1305–1290 Ma Fraser Zone is dominated by amphibolite to granulite facies metagabbroic rocks that impart a distinct, high gravity signature. The Fraser Zone is presently in fault contact with the Biranup Zone (e.g. along the Fraser Fault in the south), but limited U–Pb data indicate inheritance of zircons with ages similar to those in the Biranup Zone (Fig. 2). These data imply a spatial connection at c. 1300 Ma, which is consistent with the shared uplift history recorded between Stages I and II. In contrast to the Biranup Zone, there is no geochronological record of Stage II activity in the Fraser Zone (Fig. 2), although it is possible that major structures such as the Fraser Fault may have placed these rocks at a higher structural level that was not favourable for zircon growth.

The exposed section of the Fraser Zone in the south is dominated by the Fraser Range Metamorphics, a sheeted complex of gabbroic to granitic rocks that appear to have intruded and migmatized pelitic to calcic metasedimentary rocks. These rocks have all undergone granulite-facies metamorphism close to the time of intrusion, indicating that they represent a thick piece of hot mafic crust (a lower crustal hot zone) that has been structurally modified. Previous interpretations have suggested that the Fraser Zone represents a collage of remnant magmatic arcs (Condie and Myers, 1999), which fits with the known lithologies, although more geochemical data are required to verify this hypothesis.

The scene at Tropicana

The Tropicana–Havana gold deposit lies just east of a major northeast-trending fault marking the edge of the Yilgarn Craton (Fig. 1). The deposit lies within a zone of dominantly northwest-trending magnetic highs cut by northeast- to east-trending shear zones and mafic dykes, and within a northwest-trending, moderate gravity anomaly. The gold is reported to be hosted by Archean garnetiferous gneiss and K-feldspar-rich quartzofeldspathic gneiss (Doyle et al., 2009). However, on a regional scale, the surrounding lithologies are dominated by northeast-trending Biranup Zone metagranitic rocks, including an extensive suite of metasyenogranites mingled with metagabbro. Minor occurrences of metamorphosed mafic to ultramafic rocks and banded iron-formation are suggestive of Archean greenstones, although other interpretations are feasible. Possible scenarios to explain the margin setting include: (1) the Biranup Zone formed in situ along the margin of the Yilgarn Craton at c. 1680 Ma; (2) the Biranup Zone is tectonically interleaved with the reworked margin of the Yilgarn Craton; (3) the Biranup Zone contains remnants of Archean rocks that may be rifted fragments of the Yilgarn Craton, or may be exotic Archean rocks; or (4) the Tropicana area is part of the Biranup Zone and was accreted to the Yilgarn Craton margin, and the reported Archean component is inherited material.

Mineralization at Tropicana–Havana is described as syn-deformational but younger than the peak amphibolite to granulite facies metamorphic event (Doyle et al., 2009). Assuming the deformation and metamorphism are related to the Albany–Fraser Orogeny (and are not Archean), this implies that mineralization may have occurred during Stage II (c. 1215–1140 Ma), consistent with metamorphic ages in the eastern Biranup Zone (Fig. 2). However, the extent of the Stage II event in the Tropicana–Havana area is not yet fully understood.

Future work

Although significant progress on understanding the regional evolution of the Albany–Fraser Orogen has been made, there are still many unresolved problems, such as the existence and nature of any Archean components within the Biranup Zone. Geochemical analysis of rocks from both the Biranup and Fraser Zones is underway to identify and map out the magmatic suites, and to help interpret tectonic settings. The Lu–Hf isotopic composition of dated zircons from both the Yilgarn Craton and the orogen will allow a comparison of source materials, as well as indicating the degree to which juvenile material or reworked crustal sources have contributed to magmatism. Monazite dating combined with P–T–t analysis will also be used to help determine the regional extent of overprinting events. Monazite is more susceptible to dissolution than zircon, so is more likely to record the overprinting history rather than inheritance. These results will be interpreted in conjunction with structural and geophysical data to provide a greater understanding of the relationships between the tectonic assemblages. Although the exploration model of reworked Archean gold may be sound, alternative models, based on the current regional dataset, should also be considered.

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REE, lithium, potash, and phosphate mineralization in Western Australia

by DJ Flint

Rare earth elements

The not-so-rare rare earth elements (REE) have become strategically important globally — the former Chinese premier, Deng Xiaoping, once said 'The Middle East has oil. China has rare earths' (Dowling, 2010). Along with many other uses, REE are components of many modern electronic products including flat-panel displays, hard-disk drives and iPods. China currently supplies 95% of the world's rare earths, but is restricting supply. New significant resources to supply the rest of the world in the near term are limited, and Western Australia (via the Mount Weld REE–tantalum–niobium–phosphorus project) is positioned to meet the growing demand (and expected supply shortage) for these elements. The Mount Weld REE–Ta–Nb–P carbonatite was discovered in 1988 and partly developed in 2008, but problems with continuity of funding arose during the global economic crisis in early 2009. Control of the project owners — Lynas Corporation Ltd — almost passed to the China Nonferrous Metal Mining Group, but was refused by the Australian Foreign Investment Review Board. The Central Lanthanide deposit at Mount Weld is estimated to contain resources totalling 12.2 Mt at 9.7% REO at a cutoff grade of 2.5% REO, yielding 1.18 Mt of contained REO. The Central Lanthanide deposit contains predominantly light REO from CeO_2 (46.7%), La_2O_3 (25.5%), Nd_2O_3 (18.5%), Pr_6O_{11} (5.32%), Sm_2O_3 (2.27%), to Eu_2O_3 (0.44%), together with minor proportions of heavy REO: Dy_2O_3 (0.124%), and Tb_4O_7 (0.07%) (Lynas Corporation, 2010). Other known REE prospects and their settings include Cummins Range (carbonatite intrusion), Cundeelee (alkaline ultramafic intrusion with carbonatitic affinities), Brockman (trachyte and related tuffs), Yangibana (dykes and sills of carbonatite and fenitized rocks, with iron oxide veins containing uranium and REE; Pirajno, in prep.), and John Galt, which is xenotime in lithic quartz sandstone of the Proterozoic Red Rock Formation (Fetherston, 2008).

Lithium

The light metal lithium is another commodity in high demand in recent times, with interest particularly driven by its use in lithium-ion batteries for electric vehicles (broadly speaking, the mobile energy storage industry). Western Australia has a long history of lithium production from spodumene pegmatites at Greenbushes and Ravensthorpe (Mount Cattlin). Talison Lithium Ltd, from mining at Greenbushes, is the world's largest producer of lithium minerals. The Greenbushes pegmatite contains up to 50% spodumene, but averages 3.5%–4.5% Li_2O. Recent annual production of spodumene concentrate from Greenbushes is at the rate of approximately 200 000 tpa of various grades; low-grade products are of >5.0% and >6.0% Li_2O, with a high-grade product of >6.4% Li_2O (Miller, 2009). Much of Western Australia's past production of spodumene was treated in China to produce lithium carbonate — for feedstock for the chemical industry. This is the same route being taken for the new Mount Cattlin lithium–tantalum mine owned by Galaxy Resources Ltd. The mine, which is under construction, has global resources totalling 14.4 Mt at 1.08% Li_2O and 153 ppm Ta_2O_5 (Galaxy Resources, 2010). In late 2009, Haddington Resources Ltd announced the discovery of a lithium–tantalum pegmatite, with rock-chip sampling results up to 5% Li_2O. The discovery was in the Pilbara at Pilgangoora, in the vicinity of historic tin–tantalum mining (Haddington Resources, 2009). About 80% of the world's lithium is obtained from continental salt-lake brines in South America, and Australia's first lithium of this style was found by Reward Minerals Ltd in 2008 at Dumbleyung, extraordinarily while exploring for potash. The brines contain 530 mg/L lithium and 1000 mg/L potassium (Reward Minerals, 2009), with the lithium grade comparable to the average resource grade of the Atacama (Clarke, 2009). Western Australia also has potential for lithium-rich clay (hectorite) in a similar setting as bentonite, that is, as secondary clays in paleodrainage channels and lacustrine environments.

The fertiliser elements — potassium and phosphorus

Australia currently does not produce potassium minerals and imports about 50 000 t of potassium sulfate annually. Australia moved a big step closer to its first potassium mine after the discovery by Reward Minerals Ltd – Holocene Pty Ltd in 2006 of potassium-rich brine at Lake Disappointment, 300 km east of Newman, with average brine grades of around 3.17% K_2SO_4 (Fetherston, 2008). However, 2009 was disappointing as agreement could not be reached with the Martu people, the Native Title Tribunal decided against the grant of a mining lease, and an appeal to the Commonwealth Attorney General was unsuccessful (Gregory, 2009).

Potassium is found within evaporitic sequences, either in modern playas such as Lake Disappointment, Lake Auld (450 km east of Newman), and Lake Mackay (bordering the Northern Territory) or in older buried evaporitic sequences, such as the Yaringa Evaporite Member of the Dirk Hartog Formation (Southern Carnarvon Basin). Reward Minerals now has substantial inferred resources at Lake Mackay (20 Mt of contained K_2SO_4). Historically, Western Australia has produced potassium from alunite (potassium aluminium sulfate) at Lake Chandler (near Merredin) during the 1940s and the deposit is currently being assessed by ActivEX Ltd.

There are 85 sites of known phosphorus mineralization in Western Australia, in addition to the indurated guano (rock phosphate) of Christmas Island. The geological settings of these sites range from apatite within carbonatite and in overlying regolith (e.g. Mount Weld, Cummins Range), phosphate nodules in marine sediments (e.g. Langey Crossing and Liveringa in the Paleozoic of the Canning Basin; at Cardabia and Wandinny Dam in the Cretaceous of the Carnarvon Basin south of Exmouth; and at Wagon Creek in the Paleozoic Southern Bonaparte Basin), glauconite in marine sandstones near Dandaragan (North Perth Basin), variscite in hydrothermal veins (Mount Deverell in the Edmund Basin), apatite in layered mafic–ultramafic intrusives (Balla Balla in the Pilbara), and recent guano from sea birds, bats, and even wallabies (found in Jingemia Cave and Jurien Bay Cave). All have been variously explored and some are marginally economic. The deposit most likely to be mined first is Balla Balla, where the apatite is a potential by-product to the iron–vanadium–titanium magnetite mineralization.

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What do the changes to the approvals processes mean to the minerals exploration and mining sector?

by

S Ellis

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The State Government has made a commitment to streamline approvals processes in order to put Western Australia on par with leading jurisdictions across the world as a destination of choice for responsible resources exploration and development.

All key approvals agencies have been tasked to translate this commitment into practical improvements to their processes to provide a more efficient and transparent approvals system that is easy to understand and navigate, and provides greater certainty, responsiveness, and coordination.

This brief summarizes the projects and priorities for reform in a number of areas across the Department of Mines and Petroleum (DMP).

The focus has been in four main areas:

- Further development of regulatory tracking systems to identify opportunities for improvement and improve certainty of process for proponents;
- Revision of inter-government agreements with other agencies to ensure a more responsive and coordinated approach across government;
- Improved guidance materials for project proponents; and
- Legislative amendments.

This work has been informed by close consultation with industry, both directly by the Department, and through an Industry Working Group that was established by the Minister for Mines and Petroleum to provide strategic advice on approvals reform. A report by the Industry Working Group was tabled in the Legislative Council in August 2009. Its recommendations have made an important contribution to the decisions that the Government has so far made on approvals reforms.

In October 2009, the Government announced significant reforms including a new lead agency framework, greater independence for the WA Environmental Protection Authority, and a suite of legislative changes to streamline approvals systems. These changes are supported by the work DMP has undertaken to date to improve its processes.

DMP is the designated lead agency for the regulation of mining, petroleum, uranium, geothermal, and carbon capture and storage activities. The lead agency role is to help the proponent through the approvals processes across government. It is intended to provide a level of service appropriate to the scale and significance of the application or project. The lead agency framework guidelines are available on the DMP website:

<http://www.dmp.wa.gov.au/documents/3Lead_Agency_Guidance_Document.pdf>

DMP is also participating with the Commonwealth and other jurisdictions in the process to respond to the Productivity Commission Review of the Regulatory Burden on the Upstream Petroleum Sector. It agrees with many of the recommendations of this Review, which mirror the steps already being taken in WA to streamline approvals and improve regulatory practice. However, it does not support the establishment of a new national offshore petroleum regulator in Commonwealth waters off the WA coast, which would remove the State from its current shared regulatory role in relation to this very significant industry.

DMP's key projects and priorities for improving its approvals processes are:

Regulatory tracking systems

During 2009, DMP developed and delivered new online systems to provide approval tracking and online lodgement services for the mining industry. Proponents can now access DMP systems through the website. These systems show whether a mining tenement application, exploration or mining activity application is under assessment by DMP or another agency, if it is on hold, and whether it has been approved, rejected, or withdrawn from the process. Proponents can print online reports of their project approval status. DMP has worked closely with proponents in the development of these systems. The feedback from proponents has been positive. DMP will continue to work with industry during 2010 to further enhance the functionality of our online systems. At a whole of Government level, an approval tracking system is being developed to allow approvals to be tracked across government agencies outside of the resource sector.

Inter-agency agreements

DMP is reviewing existing approval arrangements between other key approval agencies to further streamline approval processes. New working arrangements are being developed

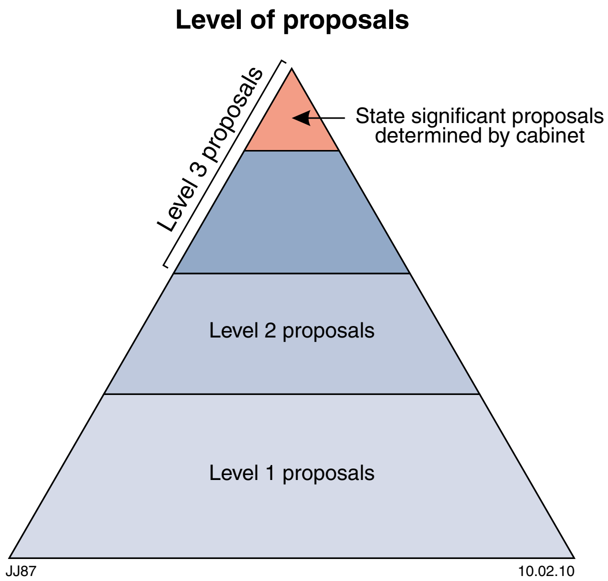

Figure 1. Notional representation of proposals in each level

between DMP and the Department of Indigenous Affairs, Department of Environment and Conservation, and the Environmental Protection Authority. In June 2009, a new Memorandum of Understanding (MOU) was signed between EPA and DMP. This, together with a revised schedule, provides more recognition of the controls under the Mining and Petroleum Acts for handling resources applications as well as clarity as to what projects will be referred to EPA thereby improving certainty for industry. Industry was consulted in the development of the new MOU.

Guidance materials

DMP has embarked on a series of administrative initiatives to streamline resource sector approval processes including new checklists and guidelines for key approval processes. Clear checklists and guidelines promote quality industry applications. High-quality applications reduce overall approval timelines. Revision of DMP guidelines for key approval processes is ongoing. DMP has also published target timelines and approval performance measures for key mining and petroleum approvals. These performance measures published quarterly show a trend of improved performance across 2009. They are available on the DMP website.

Legislative amendments

A series of legislative amendments to relevant Acts aimed at streamlining approval requirements have been tabled in Parliament. The Approval and Related Reforms No. 1 (Environment) Bill and the Approval and Related Reforms No. 2 (Mining) Bill 2009 provides amendments to remove duplicative and redundant appeal points, clarify the requirements of Section 41 'Implementing a proposal', provide for the lodgement of mineral tenements at any mining registrar within the State, and clarify mine-closure planning requirements. This will further streamline approval processes and add more certainty to the process.

Lead agency arrangements

In implementing the lead agency framework, DMP is offering different levels of service and assistance for proponents depending on the nature and scale of application or applications. Figure 1 represents a notional representation of lead agency service levels. The majority of mining and petroleum tenure and activity applications received by DMP would be characterized by service level one. At this level DMP will ensure clear guidelines and checklists exist, applications are assessed against published target timelines, and proponents have access to online lodgement and approval tracking systems and services. DMP will monitor approval progress and provide pre-proposal consultation advice and support to proponents as required. Where applications cannot be dealt with against published timelines or, for a variety of reasons, where a more urgent assessment is required, a higher level of service will be provided. In addition to normal services, DMP will consult with the proponent and other agencies and may provide a project coordinator to assist with pre-proposal consultation advice, project scoping, issue identification, escalation measures, and resolution strategies. Proposals characterized by applications or proposals that are more complex and require multiple concurrent approvals will be handled with a higher level of service. For example, DMP has assigned a project coordinator to coordinate uranium mining project approval requirements. DMP will, where appropriate, provide a referral and introduction to other relevant departments.

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