Yilgarn Retrospective

2-DAY SYMPOSIUM

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EXTENDED ABSTRACTS

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Jenny Bevan, Mick Elias and Julian Vearncombe

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Yilgarn Retrospective

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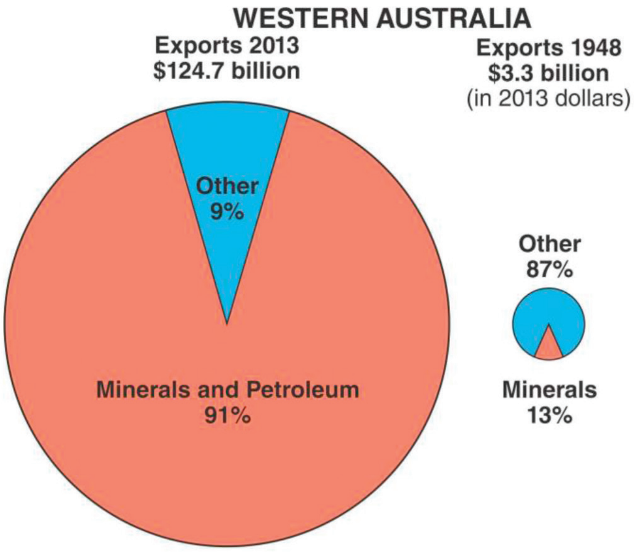
Introduction: Yilgarn Retrospective

JULIAN VEARNCOMBE[1] , JENNY BEVAN[2] and MICK ELIAS[3]

This volume is about what we learned from the highly successful period of exploration 1950 to 1999, with implications for the challenges of the future.

The Yilgarn Craton (Western Australia) in the second half of the 20th century witnessed a transformative period in the resources industry which included the discovery and successful exploitation of a new deposit type (komatiite-hosted nickel sulphide), a massive boom in exploration and mining of Archaean lode gold, and developments in a number of other commodities. The Yilgarn has a world-class endowment in nickel, gold, bauxite and tantalum, and significant iron ore, uranium and copper-lead-zinc–silver deposits. By 1999, twenty million tonnes of nickel were identified, and the gold inventory rose in 20 years from 4 million ounces to 100 million ounces, despite the mining of about 100 million ounces over the same period. Nickel production reached 170,000 tonnes per annum and gold production was ~6.5 million ounces per annum. Western Australia was converted from a small economy based on agriculture to the world's mining powerhouse. These commercial successes spawned research yielding new deposit models, a new appreciation of the regolith that blankets the Yilgarn and the tools to work beneath that regolith. This two day symposium will look at the who, why and how of this momentous era 1950 to 1999. The meeting will review the importance of what we have learned from this highly successful period, with implications to the challenges of the future, and be an acknowledgement of the achievements of teams and individuals, some of whom are no longer with us.

The Yilgarn Craton is the large southern part of Western Australia including the gold mines from Norseman, Kalgoorlie to Wiluna, Meekatharra and Boddington, nickel from Ravensthorpe to Kambalda and Leinster, bauxite (aluminum) ores in the Darling Range, copper-zinc at Golden Grove, tantalum at Greenbushes, iron ore at Koolyanobbing, and uranium at Yeelirrie.



These figures corrected to 2013 dollars show the phenomenal growth from 1948 to 2013 and importance of mining in the state of Western Australia. (In 1948 dollars the circle for 1948 would be much smaller.) The circles are scaled for area. From the symposium presentation by Phil Playford.

This meeting brings together a remarkable group of players from industry, academia and government who contributed to the success of this era. Speakers with an industry focus include Roy Woodall, Jeff Gresham, Ron Manners, Neil Phillips, Dennis Gee, Colin Agnew, John Chappell and Jim Ross, those with a government focus Tim Griffin, Phil Playford, John Bunting, Ray Smith, Megan Clark and Stephen Wyche, prospector Clive Daw, consultants Tom Bateman, Jack Hallberg and David Isles, and from academia Mike Lesher, Simon Wilde, Neal McNaughton, Ray Binns and David Groves. Speakers will look at what mattered most to shape the discovery record, and address the question of how to apply these concepts to ensure future exploration success.

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2. University of Western Australia
3. CSA Global

Biographies

JULIAN VEARNCOMBE is a graduate of the Universities of Leeds and Wales (Swansea College). He is an economic geologist with 30 years experience working across the value chain of the mineral resource industry, and on all continents except Antarctica. His energetic and varied career includes academia, technology development, consultancy, management and as a Director of publicly-listed companies. Julian has expertise in precious, base and strategic metals, with experience in executive and strategic management, public listing, capital raising, and the identification of key projects. He has been a member of teams that identified more than eight million ounces of gold and, recently, one of the world's largest tungsten resources.

A significant focus of his working career has been the application of effective structural geology to mineral exploration and mining. He is the owner and Managing Director of Perth-based SJS Resource Management, a company that specializes in all levels of exploration management, geological contracting, and through geosymposia.com.au staff training and symposia. He has co-authored more than seventy peer-review publications, and with colleagues is currently authoring a series of review papers on applied structural geology. He is an editor of the journal Applied Earth Sciences, the Transactions of the AusIMM and IMMM, and is active in the Australian Institute of Geoscientists (AIG).

JENNY BEVAN, having studied for an Honours degree in Geology at Exeter University and as a postgraduate in Geochemistry at Oxford University, then spent 12 years working in London's Natural History Museum as a petrologist, mineralogist, electron microprobe specialist and geochemist, before she left to start a family.

She emigrated to Perth with her family in 1985. Jenny eventually returned to work, first as a mineralogist and subsequently as a palaeontologist, in the Western Australian Museum. Later she was asked to take over the Earth Science Museum at the University of Western Australia, during which time she extended her general geological knowledge and skills in scientific communication and continued to research and publish, as well as teaching. In addition to scientific papers, she has also published, with John Glover as senior author, the books *Geological Journeys: from Artifacts to Zircon* and *The Forgotten Explorers: pioneer geologists of Western Australia, 1826-1926.*

She retired as Senior Curator of the E de C Clarke Earth Science Museum, after 13 years, in 2010. She is now an Honorary Research Fellow at UWA and a Research Associate at the WA Museum.

MICK ELIAS has 40 years' experience as a geologist working with the Geological Survey of WA, WMC Resources and is currently employed by mineral resource consultancy CSA Global. After graduating from the University of Melbourne in 1973, he spent 5 years regional mapping in the Yilgarn Block with GSWA before joining WMC in 1979. In his 21 years with WMC his roles covered exploration, mine geology and management at the Kambalda Nickel Operations followed by management and business development roles with the nickel division in Perth. At CSA Global he is Principal Consultant - Nickel specialising in evaluation and development of nickel laterite projects world-wide.

Consolidating the Golden Mile: How the Big Pit Happened

COLIN J. AGNEW[1]

In early 1987, the orebody underlying Kalgoorlie's Big Pit was contained in two adjoining leases, one held by North Kalgurli Mines Limited (NKM) and one held by a quasi-joint venture, Kalgoorlie Mining Associates (KMA), of which Homestake Gold Australia had a 50% interest and the remaining 50% was held by Kalgoorlie Lake View (itself in turn owned 50% by Gold Mines of Kalgoorlie Limited and 50% by Normandy Australia Limited).

The NKM section of the orebody was mined by open-cut methods with a head grade of about 3.5 g/t whilst the KMA portion of ore was extracted by underground techniques at about 13.5 g/t.

Two things were necessary to create the Big Pit at that time:

- redefinition of the underlying orebody to support an open-cut operation.
- consolidation of the corporate entities, which had to include an interest by NKM.

The open-cut experience of NKM provided confidence that the KMA portion would support a large-scale surface mining operation.

Until October 1987, the financial markets were in a state of irrational exuberance and gold assets were grossly overvalued, but this state of financial euphoria provided the means for Alan Bond to establish a corporate structure which was able to develop the orebody as an open-cut operation with associated treatment facilities. Subsequently the ownership structure has undergone changes to the extent that not one of the existing corporate entities retains an interest in the project.

Biography

COLIN AGNEW was Chief Executive for BondGold Australia, the management arm of the Bond group of gold companies at the time of the creation of the Big Pit at Kalgoorlie in the late 1980s.

He has a degree in mining engineering from the University of Queensland, conferred in 1966 together with a Masters degree in Business Administration from Sloan School, MIT, gained in 1980.

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Introducing Metamorphism to the Eastern Yilgarn

RAYMOND A. BINNS[1]

Unlike in the South Western Terrane with its gneisses and granulites, metamorphism was a largely neglected topic in the Eastern Goldfields when David Groves and I joined the University of Western Australia (UWA) in 1971, late in the 'Poseidon nickel boom'. Influenced by common preservation of field structures and microfabrics in mafic greenstones, mappers there tended to use rock names referring to presumed origins rather than present-day characteristics (e.g. 'basalt' rather than 'amphibolite'). This risked conceptual assessments of mineral deposits and their settings that could be wrong or at least incomplete, especially when the role of deformation was also neglected.

During an early visit to the Windarra nickel deposit we recognised the severity of metamorphic recrystallization and penetrative deformation (Fig. 1). Accordingly we formulated a research proposal "Metamorphism and Nickel Mineralisation in Western Australia", to be conducted from 1972 to 1975 with funding from the Australian Mineral Industries Association (AMIRA), the Australian Research Grants Committee (ARGC), and the UWA Research Committee. The work extended with subprojects and student theses to around 1980. Our aims were to establish the extent to which metamorphism and associated deformation might themselves be ore-generating processes (for instance by sulfidation of trace nickel from precursor rocks during recrystallization or by concentration of disseminated into massive ores by shearing and remobilisation) or alternatively whether their chief consequence was to simply modify original 'magmatic' sulfides deposited from immiscible liquids within ultramafic hosts. Either way, the research conveyed significant implications for exploration strategies. The funding enabled vital appointments of Bob Gunthorpe and Finn Barrett, provided funds for field travel, sample preparations, and chemical and electron probe analyses, and partially subsidised student projects.

Our work program consisted of (1) petrogenetic, mineragraphic, and geochemical investigations of representative ores and host rocks from numerous nickel deposits and exploration tenements throughout the eastern Yilgarn, conducted particularly with Honours and MSc students, and (2) extensive traversing of greenstone belts to develop an appreciation of regional metamorphic patterns and other features relevant to their evolution. With only early edition 1:250,000 topographic sheets and preliminary BMR aeromagnetic maps to guide us, no navigation apart from compass and no radio contact to base, the regional fieldwork was quite adventurous. Parallel PhD investigations of granitic rocks (Leigh Bettenay) and structural geology (Nick Archibald at Kalgoorlie-Norseman and Lars Anderson at Diemals) were incorporated in the project. Martin Gole contributed PhD research on metamorphosed iron formations, Ken McQueen on the Widgiemooltha area and its Ni deposits, and Mike Donaldson on metamorphism of dunites and their Ni ores. Rod Marston and Mike Gorton joined late in the project, the latter for Rb-Sr geochronological studies of Diemals granites in collaboration with John de Laeter. An extensive program of electron probe analyses of metamorphic assemblages in mafic and ultramafic rocks spanning very low to high grades conducted by myself and Finn Barrett remains unpublished.

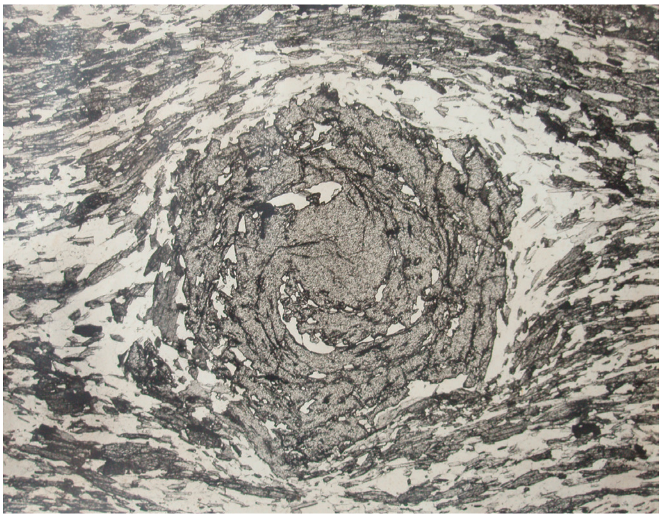

Figure 1. "Snowball" garnet in amphibolite at Windarra, delineating deformation and high grade recrystallization that also affected the adjacent nickel sulfides.

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Compiled initially for sponsor companies, in 1975 a metamorphic map of the eastern Yilgarn Craton (Fig. 2) based on some 5000 thin sections from around 1500 sites was presented internationally (Binns et al., 1976). This covered the Southern Cross, Kalgoorlie, and Kurnalpi Terranes of today's nomenclature, but not the poorly exposed Burtville Terrane in the far east apart from the Duketon area. Four domains of increasing metamorphic grade (very low, low, medium, high) covering two broad structural styles (static, dynamic) were delineated in what was necessarily a first-pass investigation dominated by data on mafic and ultramafic rocks with lesser information from pelitic or semipelitic rocks, felsic volcanics, and iron formations. Regional-scale static or low-strain metamorphism in the interiors of greenstone belts, where lower grade domains often correspond to gravity highs, ranged from (rare) prehnite-pumpellyite facies through greenschist to mid amphibolite facies. Although local cleaved zones occurred, especially in sediments and pyroclastic units, most static-style mafic and ultramafic rocks remained massive and exhibited well-preserved microfabrics despite complete or near-complete recrystallization. Linear belts of ductile, dynamic-style metamorphism, occupying many but not all greenstone belt borders, were characterised by penetrative foliations and generally elevated, high amphibolite facies and rarer granulite facies mineral assemblages, although some relatively massive boudins were retained. The two deformational styles were gradational, with no field or microscopic evidence of superimposition, thus favouring coeval development within contrasted temperature-stress regimes. At the scale of mapping, the grade domain boundaries were somewhat generalised but approximated to isograds. We recognised localised, late-stage retrograde alteration, especially in ultramafic rocks, and 'contact' or 'thermal' metamorphism producing hornblende hornfels and olivine-pyroxene hornfels from mafic and ultramafic lithologies at the contacts of post-tectonic granites or Proterozoic dykes and in the hanging wall of major extensional faults. However, we did not attempt to construct a sequence of metamorphic events (M1, M2 etc.) applicable throughout the region.

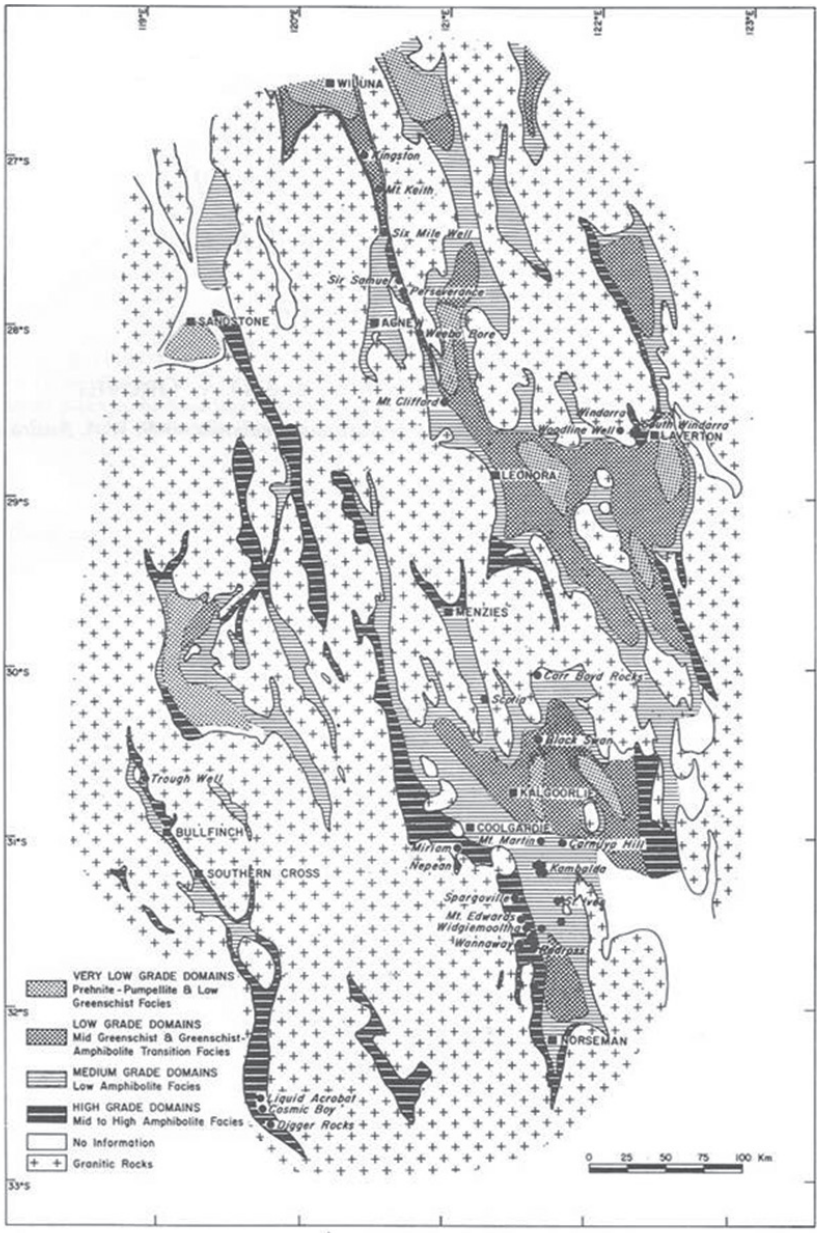

Figure 2. Metamorphic map of the eastern Yilgarn (Binns, Gunthorpe and Groves, 1976)

Binns et al. (1976) noted a contrasted distribution between low and high grade areas of rare relic igneous phases in mafic and ultramafic rocks which implied non-progressive metamorphism where metamorphic temperatures were imposed relatively rapidly on essentially unaltered sequences, and where higher grade areas had not significantly passed through a prior phase of lower grade recrystallization. From this and certain other observations we drew geotectonic inferences amplified by Archibald et al. (1978), who related the metamorphic patterns to granititoid types and their distribution, and to a 4-stage deformational history (D1 to D4, the last represented by major faults). They concluded that metamorphism was imposed on previously deformed (D1-D2) but relatively unaltered sequences, synchronously with a third phase (D3) of deformation most prominently developed in the elongate dynamic-style belts. The latter were also characterised by diapiric intrusion of synkinematic granitoids possibly responsible for uplift of dynamic belts from deeper levels relative to adjacent static-style domains. Banded gneisses and migmatites found as enclaves in synkinematic and post-kinematic granitoids and containing evidence of pre-greenstone deformation were considered modified relics of a sialic basement. Archibald et al. (1978) inferred an extended 'mantle plume'-like event responsible for mafic and ultramafic volcanism in developing greenstone belts, for the heat causing their metamorphism, and for generation of the granitoids by anatexis of basement gneisses. They and Groves et al. (1978) discounted a role for subduction and favoured development of greenstone belts in ensialic rift zones bounded by crustal fractures now reflected by dynamic-style metamorphism, although the mechanisms causing deformation in such a model were unclear, and the possibility of a continuous greenstone cover could not be ruled out.

Our project demonstrated that metamorphic and deformational processes played a most significant role in creating the presently observed characteristics of Fe-Ni sulfides in Yilgarn ultramafic hosts (Barrett et al., 1977). Their effects were largely to modify former magmatic sulfides although there are limited situations, such as within metasomatic reaction zones at the contacts between ultramafic rocks and contrasted lithologies, where chemical diffusion during metamorphism had itself generated Fe-Ni sulfides. Possibly as a consequence of a stratigraphic control, most volcanic-type ore bodies occur in amphibolite facies domains, generally of dynamic style although Kambalda is in a static-style host-rock environment with shearing focussed within massive sulfides. Metamorphic temperatures would have caused reversion of 'magmatic' sulfides to monosulfide solid solution (mss) -dominated bodies highly susceptible to ductile deformation and subsequent annealing. Typical consequences are remobilised ore shoots subparallel to fold axes, development of a microlayering defined by chalcopyrite or pyrite that is equivalent to foliation, and formation of recrystallised tectonite fabrics.

While we had not substantiated metamorphism as a significant direct generative process for nickel sulfide mineralisation, our 1976 metamorphic map and project publications established a sound background for further work in the eastern Yilgarn, and raised the profile of metamorphism amongst students, explorers, mappers and researchers in the following decades. In the 1980s and 1990s more closely spaced investigations of metamorphism in specific areas were included within the regional mapping programs of the Geological Survey of Western Australia (e.g. Ahmat, 1986: Mikucki and Roberts, 2004). An important conclusion was that the wallrock alteration assemblages associated with Yilgarn gold deposits varied mineralogically in parallel with regional metamorphic grade (Witt, 1991), implying that elevated temperatures associated with the major metamorphic event persisted some time beyond regional deformation to when the main phase of structurally-controlled gold-depositing hydrothermal activity occurred.

The next major advance, some 30 years after the UWA project, came with formation of the Predictive Mineral Discovery Cooperative Research Centre (pmd*CRC) and commencement of an Eastern Goldfields program including inter alia Geoscience Australia personnel. Extensive field and laboratory research led to robust and considerably more detailed assessments of the deformation history and metamorphic evolution of the eastern Yilgarn (excluding the Southern Cross Province but including the far eastern Burtville Terrane). From observations in pits at mine sites (many from the recent gold boom), and with the benefit of deep seismic reflection surveys and more precise radiometric dating of granites, Blewett and Czarnota (2007) and Blewett et al. (2010) developed a detailed deformation history with many extensional and compressional events (D1 to D6 or D7), involving interrelated granite emplacement, folding, formation of late sediment-filled basins, faulting, and episodes of gold mineralisation. Deformation and metamorphism of late sediment basins was considered to postdate that of the greenstone sequences. Czarnota et al. (2010) inferred a west-dipping subduction zone placed east of the eastern Yilgarn craton, based on perhaps dubious evidence.

In a very detailed assessment of metamorphic evolution based extensively on thermodynamic pressure-temperature-time estimates for pelitic assemblages, Goscombe et al. (2007, 2009) delineated five metamorphic events (Ma, M1, M2, M3a, M3b), of which M2 and to some extent M3a correspond to the granite-influenced regional patterns described by Binns et al. (1976). M1 was an inferred higher pressure dynamic metamorphism at the highly sheared major margins of greenstone belts (the crust-penetrating Isa, Ockerburry, Celia, and Hootanui Faults). Ma was an assumed arc-related granulitic metamorphism resticted to a few outcrops in the Burtville Terrane, and M3a was the proposed separate metamorphism (and deformation) of late sediment basins, although Goscombe et al. (2007) indicated M2 may overlap into M3a and the two are difficult to distinguish outside the late basins. M3b was localised hydrothermal alteration. Although also illustrating an alternative 'mantle plume' process to explain metamorphic evolution of the eastern Yilgarn, Goscombe et al. (2009) preferred a subduction-related model where the Kurnalpi Terrane represents a magmatic arc zone, and the Kalgoorlie Terrane a broad back-arc basin. This conflicts with the conclusions of Archibald et al. (1978) and Groves et al. (1978). Considering the reconnaisance nature of the UWA project, it is noteworthy that the temperature distribution patterns of Goscombe et al. (2009) for the major phase of regional metamorphism in the eatern Yilgarn conform closely to the metamorphic grade domains of Binns et al. (1976).

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Biography

RAY BINNS graduated in 1959 from the University of Sydney with a University Medal in Geology. Following PhD studies at Cambridge and a period teaching metamorphic petrology at the University of New England, he joined the University of Western Australia as Reader in Geology in 1971, teaching both igneous and metamorphic petrology and conducting the research outlined in his abstract. In 1977 he had commenced a new project on metamorphism in the Kimberley when he moved unexpectedly to CSIRO in Sydney. Administrative duties as Assistant Chief of the Division of Mineralogy and Geochemistry regrettably terminated both his Yilgarn and Kimberley work. In 1985 he returned to the bench and started a new research career on the ocean floor, discovering several massive sulfide fields rich in copper and gold in the Bismarck Sea, Papua New Guinea, one of which is scheduled for mining in 2017-2018. He is a Fellow of the Australian Academy of Technological Sciences and Engineering, and was awarded the Centenary Medal in 2001 for service to Australian geology and the minerals industry. In 2002 he received CSIRO's highest award, the Chairman's Medal. In retirement he has served as a scientific consultant to several companies, chiefly in seafloor mineral resources. He is an Honorary Fellow at CSIRO, and a Visiting Fellow at the Australian National University.

Early Mapping in the Remote Eastern Yilgarn

JOHN A. BUNTING[1]

At this conference Dennis Gee has outlined the role of the Geological Survey in mapping the Yilgarn, and Simon Wilde has described the western third. My task is to describe early mapping in the eastern Yilgarn. I'll talk specifically about the area east of 120° longitude, which coincides roughly with what used to be the Eastern Goldfields Province, now Superterrane. Some of this, especially the areas around the main mining centres, can hardly be described as remote, but 40-50 years ago the bush on the Boorabbin and Lake Johnston map sheets, or the desert northeast of Wiluna, or east of Laverton was the middle of nowhere.

As this is a Retrospective, I'll be concentrating on the first-pass 1:250,000 mapping in the 1960s and 1970s. I'll leave it to others to describe the later work, except where it impinges on some of the findings from the earlier mapping.

The history of geological mapping in the eastern Yilgarn can be divided into five overlapping stages:

1. Early detailed investigations around early mining operations, with regional mapping conducted as lengthy reconnaissance expeditions – the horse and camel era, up to the Great War.
2. Continued investigations in the mining areas, including mapping, now with motorized transport. Little genuine regional mapping in remote areas during the 1920s-1950s.
3. 1:250,000 mapping, 1961-1978, using Land Rovers and aerial photos, Rb-Sr and Pb-Pb dating and crude aeromagnetic contour maps.
4. 1:100,000 mapping (1980s-present) using Land Cruisers, aerial photos, remote sensing, zircon geochronology and other isotope data, and increasing amounts of digital data (processing, GPS, digital recording in the field).
5. Since the start of the millennium, are we in a new era when mapping per se is being replaced by sophisticated remote sensing and crustal studies?

It's sobering to contemplate the methods used by HWB Talbot in the early 1900s to cover vast areas, mostly desert. The party would consist of Talbot and sometimes another geologist, plus three or four assistants and eight to 16 camels. Depot camps were set up, and traverses made using the riding camels for a radius of up to 100 miles. Previously surveyed points were rare or non-existent, so latitude was determined, fairly accurately, using a theodolite to observe the meridian altitude of stars. Longitude was estimated using prismatic compass and the walking speed of the camels. On a traverse from Laverton to the South Australian border in 1916 (Talbot and Clarke, 1917) at the end of a 500 mile (800 km) section with no known survey points, the error in longitude was only 170 chains (3.4 km).

It is difficult now, from these sophisticated digital times, to comprehend how revolutionary was the systematic 1:250,000 mapping that started in 1961 with the Boorabbin Sheet. The 23 sheets that cover the eastern Yilgarn (Figure 1) were mapped in the relatively short time of 16 years (Table 1), although it would be another six years before the final explanatory notes were published. I'll look at the evolution of geological findings, presentation and thinking over this period; but first, what was so revolutionary about the programme?

The most important innovation was the use of aerial photographs. For the first time the geologist did not have to rely on surveying techniques to locate himself. Photo navigation became an acquired skill, and a pocket stereoscope a useful instrument (many geologists developed the skill of seeing in stereo without it). Photo interpretation was an integral part of the mapping, and the geologist was no longer restricted to what he could see on the ground.

One of the big changes with the new 1:250,000 maps was how the Archean rocks were subdivided in far more detail than previously. For a while, "greenstone" was out, because of the older division into greenstones and whitestones. "Layered succession" was in, for the various sequences of metamorphosed mafic, ultramafic, felsic and sedimentary rocks, although we later reverted to the all-encompassing terms "greenstones" and "greenstone belt". The nickel boom saw an increasing emphasis on ultramafic rocks, including

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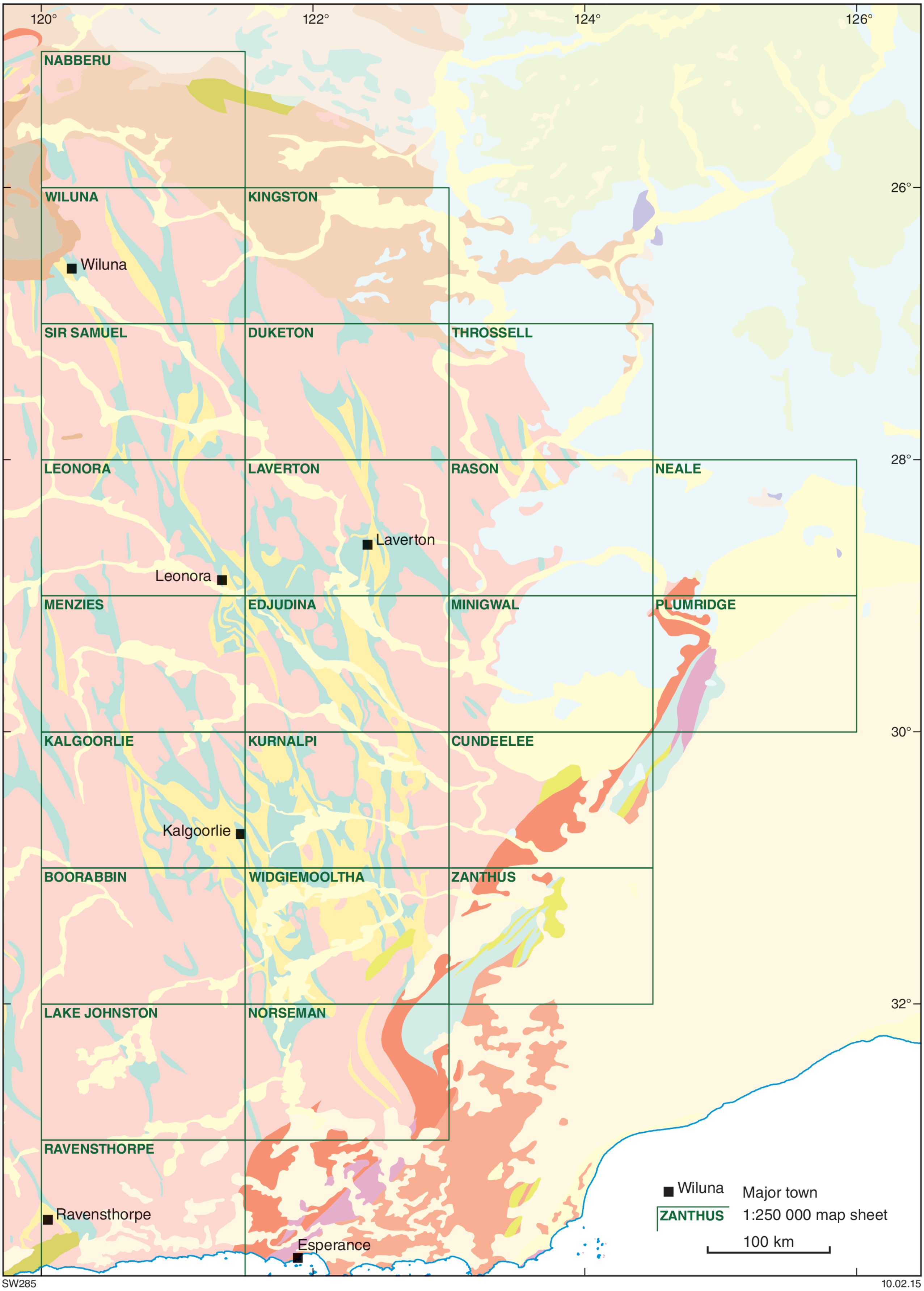

Figure 1. Location of 1:250,000 sheets covering the exposed eastern Yilgarn Craton (base map from GSWA 1:2,500,000 map). Courtesy of Stephen Wyche, GSWA.

1:250,000 Sheet	Mapped by	Map	Explanatory notes	Significance and comments
Boorabbin	J Sofoulis, W Bock 1961-62	1963	Sofoulis, 1963	First 250,000 map of eastern Yilgarn; aerial photo interpretation; 3 Cainozoic units
Widgiemooltha	J Sofoulis, R Horwitz, W Bock 1961-63	1965	Sofoulis, 1966	
Kalgoorlie	M Kriewaldt 1964-65	1968	Kriewaldt, 1969	21 Cainozoic units
Menzies	M Kriewaldt 1967	1971	Kriewaldt, 1970	26 Cainozoic units; Strat units in Archean, but not named
Kurnalpi	I Williams, J Doepel 1966-68	1971	Williams, 1970	First formal stratigraphic subdivision to Formation level
Zanthus	J Doepel, P Koehn (D Lowry) 1968	1971	Doepel, Lowry, 1970	
Norseman	J Doepel, J Newton-Smith, P Koehn 1968-69	1972	Doepel, 1973	Six named formations in Archean
Edjudina	I Williams, C Gower, R Thom, A Harley, P Koehn 1969-70	1973	Williams, Gower, Thom, 1976	Continued Kurnalpi stratigraphy northwards
Lake Johnston	C Gower, J Bunting 1971	1974	Gower, Bunting, 1976	Three named formations in Archean
Ravensthorpe	R Thom, S Lipple, 1971	1974	Thom, Lipple, Sanders, 1977	No formal stratigraphy
Laverton	C Gower, R Vogwill 1972-73	1975	Gower, 1976	Strat nomenclature abandoned on 1:250,000 map, but approx correlations in explan notes. Tectonic lineaments.
Leonora	R Thom, R Barnes 1972	1975	Thom, Barnes, 1977	No strat names on map or notes
Rason	C Gower 1972 (various mappers 1971-72)	1976	Gower, Boegli, 1977	Isolated greenstone belts
Neale	J Bunting 1972 (various mappers 1971-72)	1975	Van de Graaff, Bunting, 1975	Archean granite NW of Proterozoic, but under cover
Cundeelee	J Bunting (W van de Graaff) 1972	1976	Bunting, Van de Graaff, 1977	Isolated greenstone belts
Minigwal	J Bunting 1972 (various mappers 1971-72)	1977	Bunting, Boegli, 1977	Isolated greenstone belts
Plumridge	J Bunting 1972 (various mappers 1971-72)	1978	Van de Graaff, Bunting, 1977	Archean greenstone in Transition Zone between Yilgarn and Albany-Fraser.
Duketon	J Bunting, R Chin 1973	1977	Bunting, Chin, 1979	Strat nomenclature now informal, and not applied to map.
Throssell	J Bunting, R Chin 1973 (various mappers 1971-73)	1977	Bunting, Jackson, Chin, 1978	Isolated greenstone belts
Sir Samuel	J Bunting, S Williams 1974	1977	Bunting, Williams, 1979	No formal strat; different successions in parallel belts described in Notes.
Kingston	J Bunting 1975-76	1980	Bunting, 1980	Isolated greenstone belts
Wiluna	M Elias, J Bunting 1976	1981	Elias, Bunting, 1982	No strat names on map or notes
Nabberu	J Bunting, P Commander 1976-77 (various, 1975-77)	1981	Bunting, Brakel, Commander, 1982	**1st edition mapping of the eastern Yilgarn completed 1976**

Table 1. Eastern Yilgarn First Edition 1:250,000 Geological Maps (brackets indicate mappers involved only with post-Archaen geology).

the notion of, firstly, ultramafic magmas, then extrusive komatiite flows.

Table 1 documents the development of formal stratigraphy in the Eastern Goldfields. First introduced by Ian Williams on Kurnalpi as a series of "Associations", the final published map and notes defined the Morelands, Gindalbie, Mulgabbie, Gundockerta and Kalpini Formations for the alternating mafic/ultramafic and felsic/sedimentary associations. These were continued northwards into Edjudina. Separate formal names were set up on the Norseman and Lake Johnston Sheets. By 1972, however, Charlie Gower on Laverton and Ron Thom on Leonora were having difficulty extending the stratigraphy northwards as the greenstones separated into discrete belts defined by major linear structures ("tectonic lineaments").

By 1973-74 we had abandoned formal stratigraphic nomenclature on the Duketon and Sir Samuel Sheets when it became obvious that each of the discrete greenstone belts had its own stratigraphic succession. Further complications came because of internal structural problems within greenstone belts, and the progression eastwards into isolated greenstone belts in a sea of granite (Throssell, Rason, Minigwal and Duketon). Stratigraphic names were abandoned, and once again we had purely lithological units on the maps. Precise zircon dating and 1:100,000 mapping in the 1990s and this century confirmed the separate development of the belts, and resulted in the definition of the various terranes within the Eastern Goldfields Superterrane.

For the first time granitic rocks were subdivided, mainly on the basis of features visible in the field or thin section, such as mineralogy, texture, metamorphic effects, with only some influence by chemistry. Granite nomenclature also went through a revolution, partly reflecting confusing international fashions. Adamellite was introduced to Western Australia as a term for a granite with roughly equal amounts of plagioclase and alkali feldspar, to contrast with "granite" *sensu stricto* (alkali feldspar dominant) and granodiorite/tonalite (plagioclase dominant). In the 1980s GSWA adopted the newly defined and internationally recognized nomenclature for granitic rocks. The three subdivisions became syenogranite, monzogranite and granodiorite. Adamellite was confined to history and the confusion of recent graduates.

Mapping of the remote eastern margin of the Yilgarn in 1972-73 was particularly challenging. Beyond the sheep stations there were few, or in some cases no tracks. In 1972 Eric van de Graaff and I mapped the Plumridge and Neale Sheets, on a three-week expedition from Laverton to Rawlinna (plus a later week on eastern Cundeelee). My role was to map the Precambrian, and Eric's the Phanerozoic. Most of the area was completely unknown geologically. Some of it had no recorded visits by Europeans. There had been some mineral exploration in the late 1960s, with a resurgence in the 1990s. The discovery of Tropicana changed everything, and now the area is criss-crossed by roads and drill lines. The geology was mainly Proterozoic, but significantly we found remnants of Archean greenstone (BIF, metagabbro, metasediment) within the Transition Zone to the Albany-Fraser Province. We didn't find Tropicana – it's in a sand-covered area southwest of the greenstones. The basic tectonic subdivisions of Yilgarn to Albany-Fraser transition outlined by Bunting et al. (1976) and early Rb-Sr geochronology still bear a striking resemblance to the findings of the vast amount of excellent post-Tropicana research.

As well as aiding in the mapping of the basement rocks, the ability to see aerial photo patterns produced a major change in the nature of the maps. They became outcrop maps rather than general interpretations, and the various patterns meant that the superficial Cainozoic units could be mapped and described as never before. The first 1:250,000 map sheet published, Boorabbin in 1963, had only three Cainozoic units. Mike Kriewaldt's 1971 Menzies Sheet had 26 units. Over the next decade the situation was gradually simplified, and the last sheet published, Nabberu in 1981, had only 11. The development of subdivisions of the Cainozoic was a precursor to the later work by CSIRO, when the subdivisions were related more to weathering processes and landscape evolution. Although the first 2nd edition maps became even simpler it appears the cyclic trend has continued, with the latest 1:100,000 maps having up to 30 Cainozoic units.

Another revolution involved the availability of aeromagnetic maps. The line spacing of 1.6 km and the simple, black line contours seem crude by today's digital standards, but they were a huge advance for the time. The maps didn't have much bearing on the outcrop mapping, but they proved invaluable in the interpretation of solid geology, structure and stratigraphy, and of course had a huge influence on mineral exploration, especially for nickel.

Early gravity maps, with 11 km station spacing, had little influence on the mapping; however they had one interesting consequence. In 1972 Eric van de Graaff realized that each gravity station had a barometer-generated spot height, and we started drawing crude contours. The resulting contour map was the most detailed produced to that date of inland WA. The map not only showed, finally, that the salt lakes were linked into a series of paleo-rivers, but also that we could interpret drainage capture, tilting of the eastern Yilgarn, resultant reversal of some paleodrainages, and the multiplicity of Cainozoic shorelines on the edge of the Eucla Basin. There was a curious coincidence when our first paper was published (Bunting et al., 1974). We concurred with previous workers that "… since the Miocene little flow of water occurred in the rivers draining towards the Eucla Basin". Within weeks of the paper being published there was a storm that deposited 350 mm of rain at Pinnacles Station, near Agnew. Floodwaters flowed through Lake Raeside and Ponton Creek, before dissipating on the Nullarbor Limestone – a distance of over 500 km. A later publication (Van de Graaff et al., 1977) covered a larger area, and is still one of the few publications based on GSWA work from the 1970s covering the eastern Yilgarn to receive citations in recent literature.

Several GSWA geologists made significant contributions to the evolving knowledge of this area. The early mappers stand out, mainly because of the developments they brought to the then new concept of regional mapping – people like Jack Sofoulis, Mike Kriewaldt, and especially Ian Williams who introduced stratigraphic mapping. Dennis Gee in the mid to late 1970s also had a great influence. As head of the Regional Geology section Dennis was a great champion for the cause of regional mapping and mentor to his geological team. He could get down on his knees to inspect the detail with his hand lens, apply what he saw to the outcrop scale, and then relate it to the broader tectonic picture. I want to pay a special tribute to Charlie Gower. Charlie was one of the best mappers I ever met – systematic, original and a great teacher. He adopted the stratigraphic approach, but set it aside when it proved less applicable going north.

I would also like to acknowledge a support group of geologists whose contribution to the 1:250,000 mapping was invaluable and poorly acknowledged – the petrologists. Starting as a group under Alec Trendall in the 1960s, Robin Peers (Janse), John Lewis and others described either briefly or in detail thousands of thin sections. In 1971 Alec's replacement, the remarkable Will Libby, brought new knowledge to the Survey, which helped in identifying unusual rocks in the eastern Yilgarn. He identified shock metamorphism at what would later be described as the Shoemaker and Yarrabubba meteorite impact structures.

In conclusion, what was the contribution to the geological knowledge of the Yilgarn of the regional mapping programme? At the time it was huge, as illustrated by the hundreds of geologists who would turn up to the regular GSWA-organised excursions on the newly completed map sheets, and the sales of the maps plus explanatory notes. The mapping was regarded as being at the front end of the development of geological science in the eastern Yilgarn. With time, the increasing availability of 1:100,000 mapping, an explosion of mineral exploration, and a vast amount of research, the importance and influence of the mapping has waned. Most of us won't be around, but it would be interesting to see if a similar fate befalls current GSWA work in 50 years.

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Biography

JOHN A. BUNTING is now semi-retired after a 45+ year career in geology and mineral exploration (mainly in WA). A graduate of the University of Aberdeen, he began work in 1969 with the Geological Survey of Western Australia, where he was involved in mapping on fifteen 1:250,000 sheets in the Yilgarn and fringing Proterozoic provinces. Since 1979 he has worked for several large and small mining/exploration companies, and his own consulting company. He has published research on meteorite impact structures (including the discovery of the Yarrabubba structure) and recently helped to organize and run a field excursion to various meteorite impact sites around WA for the Meteoritical Society. In a largely voluntary role with Earth Science WA he has written field guides to the geology of the Perth region (2011) and the Capes region of southwest WA (2014) for teachers of the upper-school Earth and Environmental Science course. Work has started on the next field guide, for the area around Kalgoorlie.

Golden Grove: The Dreams, Politics and Teamwork Behind a New Mining District

JOHN CHAPPELL[1]

Golden Grove is a mining district in Western Australia with several polymetallic base and precious metal sulphide deposits in Archaean acid volcanic and volcanoclastic host rocks within a submarine basin. Mineralisation is present at several stratigraphic horizons and is associated with rift structures which were also the loci of synvolcanic dacite intrusions. The mineralisation is zoned with distinct copper-rich and zinc-gold-rich massive-sulphide lenses.

Application of a sound geological model and geological reconnaissance resulted in the discovery of the Gossan Hill deposit by Joshua Pitt and Julian Phillips in 1971. A more detailed geological evaluation and an aggressive, detailed exploration programme incorporating geochemical and geophysical surveys led to the discovery of the Scuddles Deposit and numerous mineralised prospects by the Esso Minerals team in 1979. Geological knowledge built up and developed by a small group of dedicated, observant geologists has produced a string of subsequent discoveries leaving the project in good shape with many years of future mine life, almost 50 years after the initial discovery. This has occurred throughout a period of changing corporate management and ownership.

The key to the continuing exploration success is the ability of geologists to incorporate additional data as it is acquired from new drilling and sampling, in order to reassess and refine previous interpretations and develop new drill targets. In other words, continuous detailed re-examination of the rocks and drill core is necessary to better understand the palaeoenvironments, stratigraphy, alteration and structures associated with mineralisation.

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Biography

JOHN CHAPPELL graduated as a geologist from Kings College, London, in 1965 and has since followed a career in the mineral exploration industry, working in Australia and around the world. As Exploration Supervisor, Western Australia, for Esso Exploration and Production Australia Ltd and later as Managing Director of Aztec Exploration Ltd, John was associated with the discovery and development of the Scuddles polymetallic VHMS mine and the Harbour Lights and Bounty gold mines in WA, as well as the La Choya gold mine in Mexico.

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Mineral Innovation and Future Trends that will Impact the Mining Industry

MEGAN E. CLARK[1]

The mining industry of the past decade has seen strong growth and investment fuelled by rising overseas demand and high commodities prices. Following a decade of increased capital investment in expansions and new production capacity, the recent softening in prices has led to an increased focus on the twin business drivers of increasing productivity and reducing costs across the whole value chain.

A key driver for reducing costs has been the focus on economies of scale that have stretched the boundaries of engineering. New technologies that have already made their mark in other industry sectors are now poised to transform the mining sector.

The pace of change is accelerating. The key drivers are the globalisation of science, technology and business; the investment in innovation and knowledge at a rate that exceeds GDP growth in developed and developing countries and the rapid change in data technologies. The change in data technologies is most evident in fields like radio astronomy and genetics. An example of the rate of investment is China which is expected to see a 10.1 percent growth rate in innovation and R&D versus an expected GDP growth rate of 7.3 percent in 2014 (Battelle, 2014).

The major trends that will impact the mining industry have been recently highlighted by the CSIRO (Hajkowicz et al., 2012). The key relevant trends are the relentless drive to deliver more resources from less input; balancing the changes to biodiversity and ecosystems; the shift of the global centre of gravity to Asia, the increase in digital value in every industry and the increased expectations of consumers and communities for experiences over products and for transparency and trust. The top five risks highlighted by the World Economic Forum in terms of impact are: water crises; rapid and massive spread of infectious diseases; weapons of mass destruction; interstate conflict and failure to adapt to climate change (World Economic Forum, 2015).

Within these trends and risks the following enabling technologies are particularly relevant to the minerals and resources sectors:

1. New sensors are providing an ever-growing range of information to inform end-to-end business planning. From insect-borne sensors monitoring the environment through to remote Martian sensors delivering information back to Earth, robust and relevant sensors can and will provide real-time information at an unprecedented rate. This data revolution is driven by global developments that link companies like Google with strategic national initiatives like NASA to drive change.
2. The cloud, the semantic web and automated knowledge are developing rapidly. In 2030, the web will have fully realised its Semantic or '3.0' form – where web pages are themselves computers that can communicate with each other and learn through powerful artificial intelligence algorithms. The semantic web is a lifelong, pervasive engine for the personalisation of experiences, information, services and products. It will understand you, it will anticipate your needs, in your environment, it will help you make choices and execute them for you (Leese, 2013). Data volumes and measurement will increase dramatically. However measurement and data are simply a means to an end – the real game starts as distributed data is delivered seamlessly to drive knowledge and decision-making. As these data volumes far surpass human processing ability, we can again look to other industries and adopt innovation. For example, the international Square Kilometre Array (SKA) will generate the same amount of data in a day as the entire planet does in a year. In the global market, companies are developing systems to make data universally available and to generate knowledge from that data through machine learning to solve specific challenges.
3. The 'internet of things' is expected to have 40-50 billion, connected, instrumented, intelligent devices for industrial, consumer and machine-to-machine applications by 2020, up from 15 billion now (IDC, 2013). The market will be $8.9 trillion in 2020 and have a compound annual growth rate of 7.9 percent. Mining is a physical business and so great decisions in mining operations mean nothing if they cannot be implemented – information and knowledge are useless without the ability to drive action in the real world. The 'internet of things' is now commonplace in industries like manufacturing where the real and physical worlds collide in a seamless delivery mechanism. In this world, equipment and people (including their health and state

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of readiness) is immediately transparent. This is the enabling architecture that will implement actions in the real world to drive mechanised mining operations that are progressively more autonomous.

4. Automation and autonomous vehicles are already changing the way people interact with the mine environment. Through the 'internet of things', the real and virtual worlds are connected and two discrete options emerge – both are likely over time. The industry players can use these technologies to improve the efficiency of the current mining paradigm, or drive completely different mining platforms that use variability rather than work against it by focusing on bulk averages and 'one size fits all' processes.
5. Materials and 3D printing technology will also change how we build and maintain mining systems. For example, 3D printing of high tolerance turbine blades is now a reality. On-site part printing and maintenance planning will underpin the new mechanical mining world.
6. Alternative distributed energy and storage solutions are improving. Energy solutions are always an issue for mining in remote areas and new technologies in generation and storage will increasingly complement traditional solutions.
7. Social science is a crucial aspect. In this brave new, hyper-connected world, our impact on the environment, people and social systems will be fundamentally different and a new level of transparency will be required. Water security will be increasingly significant. Opportunities for changing the way we do things will abound but we will need the tools and culture to respond. The rise of non-state actors and threats to personal and data security create new challenges. These social and environmental interactions may well be the greatest challenges.

These enabling technologies, when coupled with innovation in traditional mining technologies, are set to transform the global mining industry by 2025.

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Biography

MEGAN CLARK is a non-executive Director of Rio Tinto. She was Chief Executive of the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Prior to CSIRO, Megan held various mineral exploration, mine geology and strategy roles with Western Mining Corporation, was a Director at NM Rothschild and Sons (Australia) and was Vice President Technology and subsequently Vice President Health, Safety, Environment, Community and Sustainability with BHP Billiton from 2003 to 2008. She holds a PhD in economic geology from Queen's University, Canada and is a Fellow of the Australian Academy of Technological Sciences and Engineering, the Australian Institute of Mining and Metallurgy and the Australian Institute of Company Directors. In June 2014 she was appointed a Companion of the Order of Australia.

Megan is a member of the Australian advisory board of Bank of America Merrill Lynch, a member of the Global Foundation board and is on the advisory board of the World Economic Forum's 2015 Global Risk Report. She was a member of the Prime Minister's Science, Industry and Engineering Council from 2009 to October 2014.

A Prospector's Perspective

CLIVE DAW[1]

Clive Daw has been a full-time professional prospector since the start of the nickel boom in 1965, and worked extensively in the Yilgarn as well as in the Kimberley and Pilbara. He remembers the early days well, and concludes that prospecting in the Yilgarn in the 1960s – 1970s was much the same, in some respects, as in the 'Gold Rush' days of 70-80 years earlier. Dry blowers had been replaced by sample bags, but hand tools were the same, horses had been replaced by Land Rovers, but claims were still marked out with compass and measuring by stride. Living conditions were somewhat similar, although the author possessed an Engel fridge, one of the first in the field. Aeromagnetics represented the chief technical advance: there were no GPS, mobile phones, satellite imagery or Geodetic block applications. Computers did not come into play until the late 1970s, and everyone relied heavily on 1:250,000 topographic maps and the compass. Geological Survey Reports and geological maps were apparently scarce in the mid-1960s and only covered a few sections of the Yilgarn Craton.

After being successful in the placement of a number of claims, the author was able to afford aerial surveys. As well as information from geophysical surveys, certain types of vegetation could be recognized as good indicators of potential ground, and aerial prospecting became a speedy method of locating country worthy of close inspection. Travel in small planes was not without incident and gave rise to some close calls and amusing experiences.

The nickel boom started in the eastern goldfields of WA late in 1965 and was in full swing by 1966. It is recorded that prospector George Cowcill found a gossan at Red Hill, Kambalda. In January 1954 he had Bill Cleverly of the WA School of Mines assay the sample. Cleverly found it rich in nickel, advising Cowcill who later mentioned these results to fellow prospector and friend John Morgan. Morgan and Cowcill passed a sample on to Dr Roy Woodall, who as WMC's Assistant Chief Geologist had been assigned the task of investigating alternatives to gold mining. This Gossan fitted his new direction. He took up the challenge and won the support of WMC's Board of Directors via a submission from Sir Laurence Brodie-Hall. Dr Woodall engaged students to map and sample Red Hill. This was followed by permission to drill three holes: the very first drill hole found nickel sulphides at a very shallow depth and assayed at an incredible 8% Ni. News soon broke and the rush was on.

The rate of pegging and applications for tenements soon overwhelmed the Department of Mines, who were ill-equipped to handle the vast volume of work. They thus had the Government call an embargo on pegging in the late 60s, stopping all work in the bush. Prospectors quickly called mass meetings in all major centres, but little could be done except to apply pressure to the government of the day. Eventually the embargo was lifted, with the only apparent result of the episode being the issuing of a Miners Right for life, with no closing date, in place of the usual annual renewal.

Later the author was involved in exploration for gold and other minerals. He documents some of the complex tax and legal aspects of prospecting which he has experienced over the years, and emphasizes the role of chance in discoveries and consequent financial success. Only by luck, tenacity and thorough work are there rewards in the Yilgarn, as elsewhere, and this will always be the case. However, in his opinion the road ahead remains bright for prospecting and exploration. New technologies, aiding the industry, have allowed outstanding advances since the Nickel Boom and that progress will continue: greater finds await the intrepid prospector of the future.

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Biography

CLIVE DAW from a farming family, was born in Cottesloe in 1936 and educated in Perth and at the Denmark School of Agriculture. He spent the first ten years of his working life in the agricultural industry, but the next 15 years saw him in a range of jobs including earth moving, road haulage, mining and prospecting, the last of which took him as far afield as Russia and the USA and involved a wide range of mineral resources. The following 23 years he spent as a building engineer, property and asset manager. Although officially retiring in 2000, he soon realized he was not yet ready to do nothing, and came out of retirement to spend another five years establishing and developing a major environmental business, until eventually selling out and retiring for good. His interests have continued in exploration, both on land and under the sea. He has collected rocks and minerals throughout his life, and now specializes in microscopic minerals, and was involved in the recovery of a meteorite, the first found using the cameras of the Australian Desert Fireball Network. Highlights of his undersea exploration over the years have involved diving and discovering several shipwrecks off the West Australian Coast.

Mapping the Yilgarn

R. DENNIS GEE[1]

For my part the "Yilgarn Journey" began one pleasant Sunday afternoon in Kalgoorlie in 1970. I was refereeing a Goldfields rugby match, I think between Kambalda and Towns. Frank Lindeman (WMC geophysicist) had already scored three tries in the first half. At half time a tall gentleman came up to me and introduced himself as Joe Lord. He told me what a good job I was doing, and how pleasing it was to see the all-round strength of Goldfields Rugby. I said I was an industry geologist. Subsequently I was to give credence to the oft-stated adage that you did not have to be a rugby aficionado to get a job with the Geological Survey of WA, but it does help.

Joe Lord (then director of GSWA) was up for the Norseman Excursion, which I was to attend as an industry geologist. I also attended the subsequent Kurnalpi re-run and the Edjudina Excursion – famous for the presence of no less than 103 Land Rovers. I got to know Joe Lord rather well over this period of time: it culminated in my being offered the position of Supervising Geologist, Regional Mapping. My role was to plan and coordinate the statewide 250K mapping program in Precambrian terranes, and to ensure the geological veracity and consistency of the mapping and its products. Because of the intensity of the "Nickel Boom" some emphasis was required on the Yilgarn "Block" as it was called then.

It is well to recall the state of knowledge of Archaean geology at that time. The Kambalda deposits had been discovered by WMC, but were off-limits to industry geologists, and I suspect also to academia. Explorers were guided by gossans over magnetic anomalies. There were four-mile BMR aero-magnetic contour maps for much of the Eastern Goldfields, and virtually every magnetic anomaly, no matter what its origin, was pegged for nickel. We had just had the first Archaean Conference in 1971. I perused the "Red Book" in preparing this talk. WMC presented a standout paper on the Golden Mile (Travis et al., 1971) but was silent on the Kambalda ultramafics . All the papers addressing the ultramafics struggled with their origin. Although there were good descriptions of quench textures (Nesbitt, 1971), all presenters were hesitant to invoke a volcanic origin for peridotites. Bob Nesbitt opined that the multiple ultramafic units may be sills or flows, but noted there was no unequivocal evidence for extrusive origin. Ross Fardon (then with WMC), in an ultra-condensed abstract, nearly let the cat out of the bag by stating that "most of the Kambalda ores might have been brought to their present positions as molten sulphide pools carried at the base of flows or sills".

It is clear that WMC were well in front of all other explorers in understanding the flow zonation of the ultramafic lavas, which had important implications for nickel exploration. GSWA contributed significantly to this understanding with the paper by Barnes, Lewis and Gee (1974). This was very important to the mapping programs of GSWA, which relied heavily on sequence facings, whether they were from sedimentary structures, differentiated gabbros, or volcanic pillows. Such facings were, and remain today, essential observations in interpreting structure and stratigraphy in the Archaean. I return to this point later.

So this brings me to the GSWA Yilgarn mapping program. It relates to a decision in about 1959 of the Conference of Chief Government Geologists of Australia, which included BMR (as it was then called) to embark on systematic mapping of the entire Australian continent at a scale of 1:250K with accompanying Explanatory Notes, and generally observing agreed formats of presentation.

Beyond that, agreement was hard-fought, as this was an era of "patch warfare". BMR geologists were kept out of the mineral belts (including the Yilgarn Block) because according to then GSWA director Matt Ellis, BMR knew nothing about minerals. This policy endured in various selective forms for nearly two decades.

In 1961, incoming Director Joe Lord restructured GSWA into Regional Mapping, Mineral Resources, Sedimentary Basins, and Engineering & Hydrogeology Divisions. There were also service branches like Petrology, Geophysics, Palaeontology and Publications. He then deployed most geologists on regional mapping duties. Few were spared conscription.

Thus began modern-era standard-series geological mapping by GSWA. This presentation deals exclusively with the 250K systematic mapping program, and does not deal with the subsequent 100K maps which were to become by-products of project-focussed integrated multi-disciplinary

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geological studies. However it does acknowledge the Second Edition 250K maps that derived from the 100K mapping.

One further historical note - in 1911, well before the official starting gun, WH Talbot began systematic mapping of some of the Yilgarn goldfields at a scale of 1 inch : 300 chains. Only geologists of our generation, and cricket-ground curators, will know that a chain is 22 yards, which is 792 inches. So Talbot's scale of 1:237,600 was close to destiny. One can presume he surveyed with compass, chain and sextant. The Talbot team produced all or parts of 26 rectangles before he was unfortunately speared by aborigines, not fatally, but of such seriousness that he had to abandon the program.

The new program commenced in 1962 when Jack Sofoulis was assigned to map Boorabbin 250K Sheet, to head-off a threatened BMR invasion. Boorabbin was chosen because of the great swathes of granite and sandplain which would expedite production and demonstrate efficiency in the eyes of BMR. Jack went on to map the Widgiemooltha Sheet. In another indication of the state of play at that time, he described the enigmatic talc-carbonate-tremolite-chlorite rocks (now known to be extrusive ultramafics) as possibly metasomatised dolomite.

I joined GSWA in 1972 when 10 sheets had been mapped (Kalgoorlie, Kurnalpi, Menzies, Widgiemooltha Norseman, Edjudina, Murgoo, Yalgoo and Perenjori), mostly as pre- and syn-nickel boom products. This left another 30 sheets to complete the Yilgarn Craton. The nickel boom had severely depleted GSWA of its geological staff, which stalled the mapping program. Following the collapse of the nickel boom, momentum was regained, and with the appointment of a new Regional Mapping Supervisor dedicated to the mapping mission, GSWA finally established integrated multi-member parties, working concurrently on adjacent sheets, tackling individual tectonic units, with frequent field reviews by all involved geologists. Then ensued a decade of staff stability, high productivity, team enthusiasm and map consistency – you could call them "the glory days"!

Our modus operandi was two geologists per map sheet, each with a Land Rover and a field assistant, on weekly fly camps, and generally sharing an office caravan in a central field location. Long-range fuel tanks, spare leaf springs and stub axles were prescribed. It was a protracted battle to have refrigerators and auxiliary batteries installed into field vehicles. Field stints in the Yilgarn were three lots of 8 weeks, depending on location. This was tough on geologists, especially those with young families.

All this was done in the pre-GPS and pre-digital eras, but the methods were effective and accurate. Line work was marked in the field on stereo-overlapping air photographs at scales of 1:30K to 1:80K. Point–source observations were made by numbered pin-pricks on the reverse side of the photo and recorded in a field notebook. Stereo-view was essential for accurate field location and realistic representation of geological line-work. I had a couple of geologists who were colour blind, but that was not a real impediment because Joe's budget did not run to colour air photos. But I also had a geologist who could not see in stereo even with a stereoscope, and that was a real worry.

Line work and symbols were transposed in ink on to 50K or 100K compilation transparencies that had topographic features embedded as green lines – the veritable "green-line drop-outs". After dye-lining, the composites for the total sheet were hand-coloured by the geologist to check for consistency and closure. After supervisor sign-off, they were handed to the cartographers. Line work for each geological unit was hand scribed on to coated plastic foil for the production of colour-separation plates, of which there could be as many as thirty. Maps were printed at Mercury Press in Hobart. They were a product of exquisite beauty, of which the geologists and cartographers were very proud. Things are different today with digital capture of geological observations, and computer-drawn maps.

The strategy was immutably and unashamedly for the production of 250K maps. This caused some degree of impatience with industry geologists who wanted to see more synthesis and detailed follow-up mapping. Some industry geologists embarked on their own programs. In 1975, Bill Gemuts (Anaconda) and Albert Theron (Australian Selection) published a synthesis of the Coolgardie-Widgiemooltha- Norseman area. And Jack Hallberg and Barry Fehlberg produced "rival" geological maps of specific mineral belts, which in later life I have found to be excellent.

Joe Lord threatened not to retire till the mapping of the State was done. Although he was much admired by most of his staff, this was a real incentive to accelerate the program. By 1979, the State was 90% mapped at 250K scale, except for some awkward gaps in the middle of the Yilgarn Craton.

The productivity of the 1970s and early 1980s occurred at a time when BMR and its successor AGSO, were suffering endless reviews, the core issue being their role in regional mapping. As a consequence, their veteran mappers were loaned out to the States. Specialists in basin analysis had been engaged in the sedimentary basins, but BMR participation had hitherto been barred from the Western Australian Precambrian Shield. But in 1979 GSWA "borrowed" some first-class field geologists from BMR/AGSO to map the Youanmi and Sandstone Sheets in order to help complete Lord's mission (Stewart, 2014). That left two square holes - Kellerberrin and Corrigin - which were assigned to Richard Chin. With these two sheets the 250K mapping of the Yilgarn Craton was finished. Not by coincidence, Joe Lord retired.

Unravelling the architecture of the Yilgarn Craton (and of course other geological regions of the State) demonstrated that regional mapping was indeed worthy research in its own right. There is something glorious about regional geological mapping, in that, like an intrepid explorer, you can on any day make a new discovery. There was of course an opportunity and responsibility to make progressive syntheses of the evolving revelations.

One memorable output of this campaign was the production in 1979 of a State 1:2.5M geological map which for the first time showed a realistic representation of the greenstone-belt distribution and the major lithofacies of the Yilgarn Craton. It also portrayed the mystery of the enigmatic salt lakes of the State's interior, revealing them to be the remnants of ancient rivers flowing into long-departed seas (Van de Graaff et al., 1977). John Bunting (these proceedings) will expand on these palaeorivers that have economic importance and contribute to the geological understanding of the separation of Australia and Antarctica. I have to remark that, despite subsequent revisions that include more detailed and reliable information, the 1979 State Geological Map remains the most aesthetically pleasing in its uncluttered elegance. The map, was published at about the time that Joe Lord retired and was a fitting tribute to his leadership over a period of some 20 years.

By 1982, in time for the Second Archaean Conference, we were able to identify the major architectural components of the Yilgarn Craton (Gee et al., 1982). Mapping led by Simon Wilde in the southwest and Ian Williams in the northwest documented the integrity of the Western Gneiss Terrane (WGT), and its contrast with the granite-greenstone terrains of the greater part of the Yilgarn Craton. In amongst the copious granites and orthogneiss were belts of undoubted paragneiss and schist of siliciclastic sedimentary origin, together with remnants of large layered mafic complexes, but seemingly devoid of volcanic rocks of any type. There were several exhilarating "Eureka Moments" for the regional mappers in the WGT with discoveries of conglomerate and carbonates in the ancient gneiss at Mt Narryer, the discovery of paired metamorphic belts in the Midwest, and the discovery of an unknown greenstone belt at Mt Saddleback. It was evident at the time that the WGT in general, and the Narryer region in particular, was providing the first tangible geological evidence of a sialic basement to the granite-greenstone terrains of considerable antiquity (de Laeter et al.,1981). Subsequent geochronology confirms the very old ages of rocks and zircons. Simon Wilde (these proceedings) will expand on this.

The mapping campaign confirmed the validity of the tripartite division of the granite-greenstone terranes into the Murchison, Southern Cross and Eastern Goldfields Provinces that had been most useful for descriptive purposes since being proposed by Williams (1974). All three provinces were characterized by multi-layering of thick mafic and felsic sequences: however, each province appeared to have a unified lithology, structural history, and perhaps even contrasting stratigraphy.

Gee et al. (1982) went further to suggest that the three greenstone provinces represented separate basins in which thick but simple layered sequences accumulated. Because assimilation of greenstone by granite played no part in the vertical doming, erosion is the only process that could substantially affect the gross outline of the basins as seen on geological maps. An envelope around the main greenstone areas should therefore define the minimum extent of the greenstone basins.

Primordial Archaean crustal models and accretionary crustal models abounded at this time. Rather, the evolving picture from GSWA mapping suggested that the basins formed in broad elongate downwarps, on thin sialic crust adjacent to the conventional basement of the WGT. Only in the Eastern Goldfields Province was there evidence of concurrent tectonism with sedimentation, probably implying rift faulting. Some form of stable basement seemed to be required under the greenstone basins to preserve the layered volcano-sedimentary sequences. All the evidence, albeit equivocal, pointed to the basement being predominantly sialic. Although the ovate nature of the granitic domes provides evidence of crustal shortening (which incidentally can be measured if one assumes original domes were circular), major tectonic movements were seen to be predominantly vertical. These comments highlight two issues of the day.

Firstly, the question of basement to the greenstone sequence was, and I suspect still remains a vexed question. Although there is a large body of isotopic evidence that a sialic crust must have been present, its geological presence remains elusive. Perhaps the extensive basal orthoquartzites of Southern Cross Province still remain the best geological evidence. Such quartzite at Maynard Hills did deliver zircon populations of 3600 Ma, 3300 Ma and 2900 Ma (Froude et al., 1983).

Secondly, is the role of horizontal tectonics. I suspect our experience was coloured by the omnipresence of steep dips of foliation and primary bedding observed during the 250K campaign. Of course there is abundant mesoscopic fabric evidence for the existence of early foliation and stretching lineation, pre-dating the regional upright folds. But from all the thousand or so facings we recorded on our 250K maps, still no significant area of total overturning has been demonstrated. Maybe that was a function of the scale on which we were mapping, but I should add we endeavoured to look at every outcrop. I have recently had the pleasure of doing detailed mapping in three mineral areas in the Yilgarn for industry clients, and encountered rock distributions and structural features that can only be interpreted as early thrusts that pre-date the upright folds. These geological reconstructions come from compilations of litho-logs of thousands of exploration drillholes at the prospect scale, aided by interpolation using high-resolution aeromagnetic images in a manner that David Isles would approve. These compilations reveal multiple stacked thrusts. Deep swallow-tail terminations at the ends of BIF units are another giveaway of early horizontal structures. In retrospect, I think the thick lithostratigraphic piles of sediments and volcanics, that on some sheets were given formation names, retain their integrity, but are replete with stacked internal thrusts rather than recumbent folds. In this respect the multiple layers of thick felsic, tholeiitic and ultramafic volcanic piles still have stratigraphic significance.

The consideration of horizontal tectonics became important in the 1990s when a leading consultancy advocated an early gold mineralizing event, based on the observation of a single gold-bearing pyrite crystal enveloped by S1 foliation. I suspect this generalisation has lost its currency – and rightly so.

Finally I should add that all our mapping was done in the absence of high-resolution aeromagnetics, and precise (± 2 Ma) radiometric dating of greenstones. I look forward to subsequent presentations in this meeting that may expose the limitations of our campaign mapping, and to learn how far we have come in the 30 years since the completion of the 250K mapping program of the Yilgarn Craton.

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Appendix

GSWA (and BMR*) geologists contributing to the 250K Mapping of the Yilgarn Craton, as recorded in the Explanatory Notes

Richard Barnes	Charles Gower	Jack Sofoulis
John Baxter	Tim Griffin	Alastair Stewart*
David Blight	Arthur Hickman	Ron Thom
Albert Brakel	Mike Hunter	Bob Tingay*
John Bunting	Mike Kriewaldt	Ian Tyler
John Carter	Stephen Lipple	Ian Walker
Richard Chin	Lyall Offe*	Keith Watkins
Phil Commander	Peter Muhling	Phil Wharton
John Doepel	Rod Marston	Simon Wilde
Mick Elias	Colin Sanders	Ian Williams
Dennis Gee	Robin Smith	Steve Williams

Biography

DR R. DENNIS GEE is a geologist with more than 50 years' experience in the mining industry, government service and research management. In the latter part of his career he was Chief Executive Officer of the Cooperative Research Centre for Landscape Environments and Mineral Exploration attached to CSIRO. Previously he was the Director of the Northern Territory Geological Survey, and successfully implemented a new strategic plan to stimulate mineral exploration in the Northern Territory of Australia.

Prior to that he was Regional Manager with MIM Exploration, and Exploration Manager for Reynolds Australia Metals. Both Reynolds and MIM were top-ranking mining companies in Australia, with world-class gold and base-metal production. He served as Deputy Director of the Geological Survey of Western Australia, and supervised the completion of 1:250,000 scale regional geological mapping of the State.

He is a graduate of the University of Tasmania with BSc (Hons) and PhD and commenced his career in the Tasmanian Mines Department. He is a former President of the Geological Society of Australia. He has been a member of the Australian Institute of Geoscientists for 20 years, and is a Graduate Member of the Australian Institute of Company Directors. He has held directorships of two ASX listed companies, one of which was founding director and chairman of geothermal energy explorer Torrens Energy Ltd.

Dennis Gee has widespread exploration experience in mineral and energy commodities throughout Australia, Canada, Uruguay, Brazil, Mexico and Nigeria. Since formal 'retirement' in 2005, he has been consulting and contracting in resource exploration, covering a variety of metal, industrial mineral and coal commodities.

Kambalda: Discovery and Impact

J. J. GRESHAM[1]

Introduction

The 1950s and the early 1960s saw a rapidly growing demand for commodities. Fuelled by the post-war rebuilding of Europe and Japan, the Korean War, the building of defence stockpiles by the United States and the rapid growth of the US automotive industry the consumption of most metals was increasing dramatically. Nickel was no exception. The western world nickel production at that time was totally dominated by the Canadian producers, International Nickel Company of Canada (Inco) and Falconbridge. These two giant companies had been built on the massive nickel deposits at Sudbury in Northern Ontario. Inco had also discovered, in 1956, (Fraser, 1985) the Thompson nickel deposit within Proterozoic rocks in Manitoba. With production from Thompson commencing in 1961 the nickel market in 1965, which totalled about 316 000 tonnes of metal, was totally dominated by Canada. However a series of events were soon to dramatically change Canada's domination of the nickel industry.

Discovery

The Prospectors' Role

Western Mining Corporation (WMC), founded in 1933 had up to the mid-1950s focussed on the search for and the production of gold. However the fixed gold price and the limited profitability that the company was generating from its gold operations resulted in a change to the gold-only strategy. Commodity diversification was discussed by the Board and was formalised in the Chairman's address in 1953. A successful move was made into the aluminium business with the discovery of the bauxite deposits in the Darling Ranges SE of Perth in the late 1950s. This ultimately led to the financially important Alcoa of Australia aluminium business. A less financially important venture into iron ore was the Geraldton Joint Venture with the American companies, Homestake Mining and Hanna Mining, which saw the first shipment of iron ore from Australia to Japan in 1966. During this period exploration continued for new deposits although funding was limited and competition for funds within the exploration group was intense. There was a significant focus

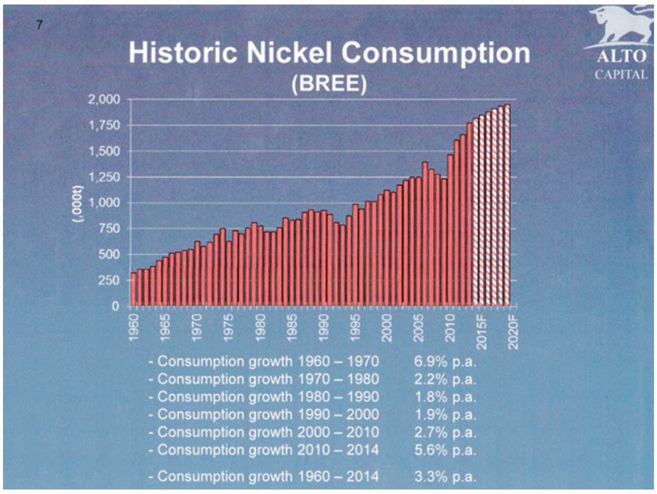

Figure 1. Historic Nickel Consumption 1960-2014

on the Proterozoic terrains of Eastern Australia but Roy Woodall, then Assistant Chief Geologist of the Exploration group, was strongly advocating for the search for base metal deposits within the Archaean rocks of the Yilgarn Craton. To this end he had initiated a mapping program to map the greenstone sequences southward from Kalgoorlie.

In late August 1964, John Morgan, who worked for one of WMC's associated companies in Kalgoorlie and was a part-time prospector brought some samples of weathered ironstone into Roy Woodall at the Exploration Office. He indicated that the samples were reported to contain traces of nickel and came from the Kambalda area about 55 km south of Kalgoorlie. Unbeknown to Woodall at that time Morgan had a prospecting partner, George Cowcill, who since 1931 had intermittently been prospecting in the Kambalda area. In 1954 and 1955 Cowcill had some samples from Kambalda analysed at the School of Mines in Kalgoorlie and the geology lecturer at the school, Bill Cleverley, reported the presence of nickel in the samples. When Cowcill became aware of WMC's interest in base metals he mentioned to Morgan that he had collected samples from Kambalda that contained nickel. He and Morgan went down to Kambalda to collect more samples and acting on Cowcill's behalf Morgan took some of these samples into Woodall.

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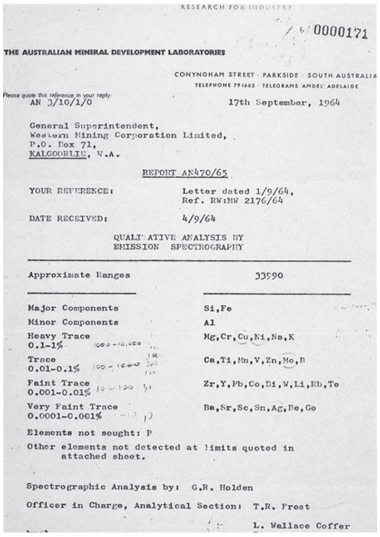
RESEARCH FOR INDUSTRY

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THE AUSTRALIAN MINERAL DEVELOPMENT LABORATORIES

CONYNGHAM STREET · PARKSIDE · SOUTH AUSTRALIA
TELEPHONE 791662 · TELEGRAMS 'AMDEL' ADELAIDE

Please quote this reference in your reply:
AN 3/10/1/0

17th September, 1964

General Superintendent,
Western Mining Corporation Limited,
P.O. Box 71,
KALGOORLIE, W.A.

REPORT AN470/65

YOUR REFERENCE: Letter dated 1/9/64, Ref. RW:MW 2176/64

DATE RECEIVED: 4/9/64

QUALITATIVE ANALYSIS BY EMISSION SPECTROGRAPHY

Approximate Ranges	33990
Major Components	Si,Fe
Minor Components	Al
Heavy Trace 0.1-1%	Mg,Cr,Cu,Ni,Na,K
Trace 0.01-0.1%	Ca,Ti,Mn,V,Zn,Mo,B
Faint Trace 0.001-0.01%	Zr,Y,Pb,Co,Bi,W,Li,Rb,Te
Very Faint Trace 0.0001-0.001%	Ba,Sr,Sc,Sn,Ag,Be,Ge

Elements not sought: P

Other elements not detected at limits quoted in attached sheet.

Spectrographic Analysis by: G.R. Holden

Officer in Charge, Analytical Section: T.R. Frost

L. Wallace Coffer

Figure 2. Amdel Report of Spectrographic Analysis of gossan sample

Woodall immediately submitted the samples to the Australian Mineral Development Laboratory (AMDEL) in Adelaide for a full spectrographic analysis. The results excited Woodall in that they showed one sample to contain about 0.5% copper as well as unusually high amounts of nickel, molybdenum, tellurium and silver. He recognised the significance of these assays and that the samples Morgan had brought to him were probably from a leached base metal sulphide gossan. The high tellurium content was typical of magmatic nickel sulphides. On receipt of the AMDEL report he immediately organised to visit the site where the samples came from with John Morgan on September 21. He found that the samples came from a series of small collapsed workings but made the important observation that these workings occurred at the contact between ultramafic rocks and basalt. This confirmed his view that the samples were gossans from a base metal sulphide occurrence. On September 23 he communicated his findings to the General Superintendent of WMC, Laurence Brodie-Hall concluding with *"I am not suggesting I have found an orebody but the occurrence is of great significance"*.

Despite prospecting the area for years Cowcill had never applied for a mining lease or other title in the Kambalda area. WMC applied for and was granted a Temporary Reserve (TR) of 52 square kilometres over the area and it was only when Woodall advised Morgan of this fact in November 1964 that he learnt of Cowcill's role in finding the samples that Morgan had brought to him. He indicated to Morgan at that time that if anything worthwhile was found his contribution would be acknowledged. WMC later granted Morgan and Cowcill each an ex-gratia payment of $25 000 for their role in the discovery.

The Explorers' Role

Following the granting of the TR a mapping program was initiated during the 1964/65 summer. Two students, John McKay and Dave Gamble, supervised by Guy Travis

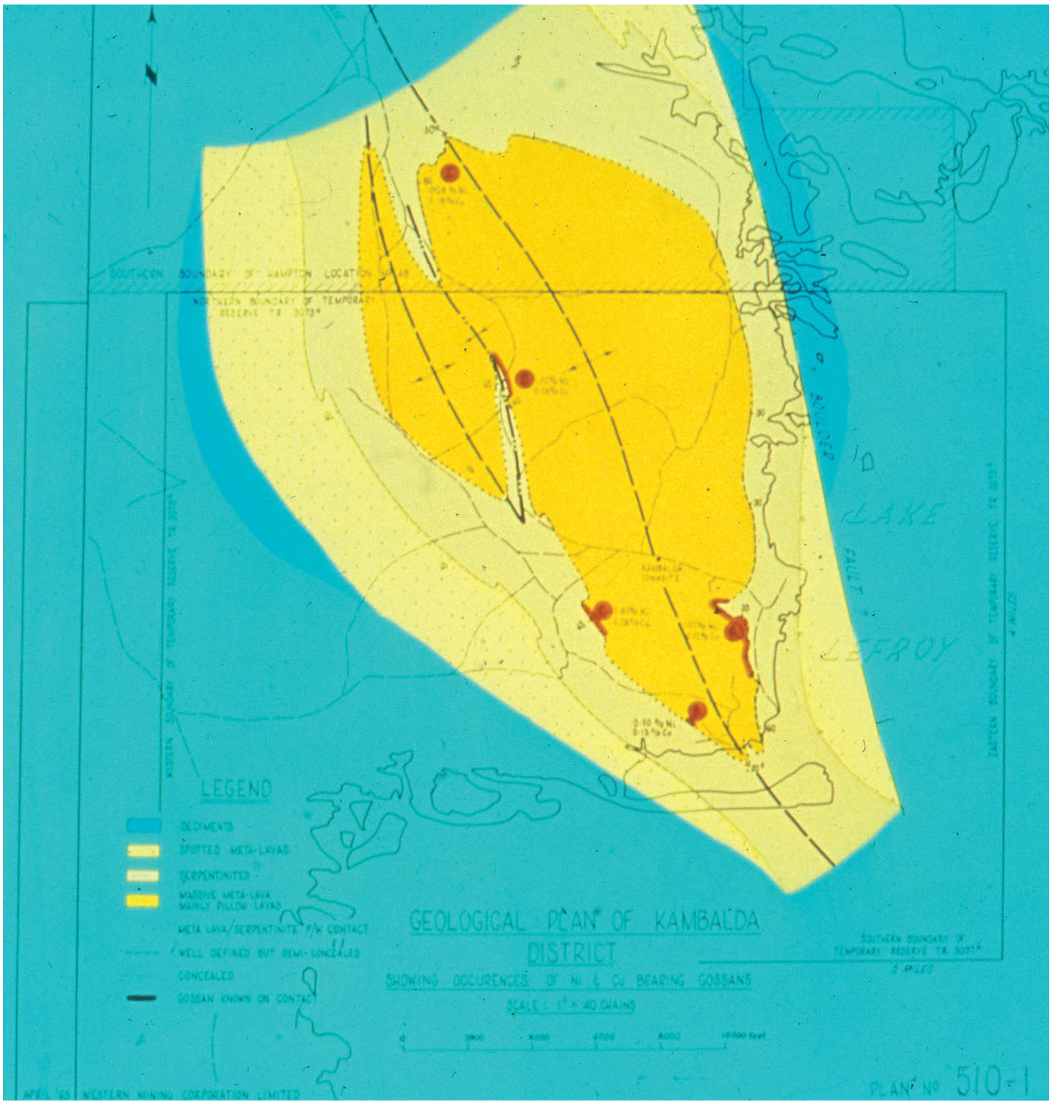

Figure 3. Map of the Kambalda Dome prepared by Guy Travis, 1965

mapped the area and defined a sequence of ultramafic rocks overlying pillowed metabasalt that formed a domal structure plunging to the north and south. Numerous other gossan occurrences were located at the ultramafic-metabasalt contact and the extensive nature of the mineralisation was clearly indicated.

During 1965 an induced polarisation (IP) survey and geochemical soil sampling, under the supervision of Anton Triglavcanin and Richard Mazzucchelli respectively, were carried out over the Kambalda Dome. Importantly, during this period of intensive, high quality, multi-disciplined exploration work WMC moved to consolidate a strong land position in the area. Another large TR was pegged to the south of Kambalda, covering the St Ives and Tramways areas. An option agreement was also negotiated with Hampton Gold Mining Areas Ltd to access ground to the north of the original TR. Finally, some 15 months after Woodall visited the site with Morgan, the first drill hole, under the supervision of Dick Elkington, was collared in late 1965 and on January 28, 1966 KD 1 intersected 2.7 metres of massive sulphides that assayed 8.3 % nickel. The first nickel sulphide discovery in Australia and the Yilgarn Craton had been made.

Impact

"The Directors announce that in exploring the Kambalda area 30 miles south of Kalgoorlie for nickel, one drill hole has intersected significant nickel sulphide mineralisation. Additional drill holes are being put down in the area but it will be some time before any evaluation of the discovery can be made"

This rather low key announcement made by WMC on February 21st 1966 would eventually lead to events that would have a huge impact on the financial markets, the level of exploration activity and discovery of further mineral deposits, particularly nickel deposits within the Yilgarn Craton, and the evolution of a genetic model for what became known as komatiite-hosted nickel sulphide deposits.

The Stock Market Boom and Financial Impact

The markets were initially slow to react to news of the Kambalda discovery but as news of continued exploration success around the Kambalda Dome became known and plans to commence mining operations were announced in April 1966 WMC's share price and the stock market in general started to climb. It was the start of the "nickel boom" (Sykes, 1978) that culminated with the Poseidon share price briefly touching $280 on February 5, 1970. Four months earlier it had been 80 cents. The inevitable crash of the market duly took place and by December 1970 Poseidon shares were back to $39 and the boom was over. However during the five-year period from the Kambalda discovery, significant funds were raised, numerous exploration companies were founded, the level of exploration activity intensified, significant discoveries were made and new mining operations developed.

The discovery transformed WMC from a small struggling gold mining company, albeit with a valuable interest in the developing Alcoa business, into a major force in the Australian mining industry. By the end of 1966 its market capitalisation had nearly doubled to $30.5 million and as the significance of the discovery became better understood, reached $114 million in 1967 and peaked at $422 million, equivalent to $2,975 million in 1999 dollars, in 1970 (A Parbo pers. comm.)

The Kambalda discovery also had a significant and positive impact on the finances and infrastructure of the state of Western Australia. This continues today.

Mineral Discoveries

The years 1966-71 were years of intensive exploration and mine development activity throughout Australia. The focus within the Yilgarn Craton during this period was for nickel sulphide deposits and numerous significant discoveries were made (Ross and Travis, 1981 and Hronsky and Schodde, 2006). WMC made further significant discoveries around the Kambalda Dome and in the St Ives-Tramways area to the south following the initial success at Lunnon Shoot. These discoveries allowed WMC to develop an integrated nickel business with smelting and refining capacity. Numerous deposits were discovered by different companies in the Widgiemooltha area to the west of Kambalda. All these properties were subsequently purchased by WMC. Smaller deposits were discovered and developed at Scotia, Carr Boyd and Nepean. The Windarra discovery by Poseidon in 1969 triggered the final, frantic, frenzied era of the nickel boom. Before the boom was over the important discoveries of Mount Keith, Yakabindie, and Leinster had been made. The graph of nickel discovered clearly demonstrates the huge exploration success achieved during this period and the lack of significant discoveries subsequently.

Komatiite-hosted nickel sulphide deposit model

Prior to the Kambalda discovery there were no known significant nickel deposits associated with komatiitic ultramafic rocks. The period from the discovery to 1999, saw the development, evolution and continual refinement of a model for this new type of deposit. This process continues today (Barnes, 2006). The model was the result of research

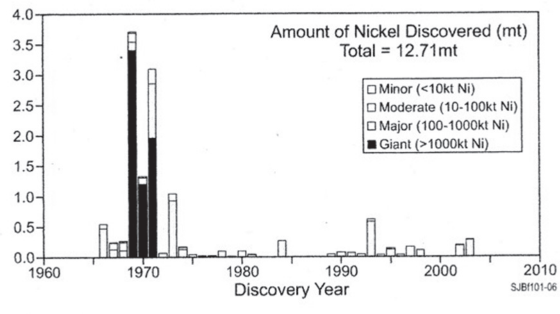

Figure 4. Nickel Sulphide Discovery history for the Yilgarn Craton expressed in terms of nickel metal tonnes discovered (from Hronsky and Schodde, 2006)

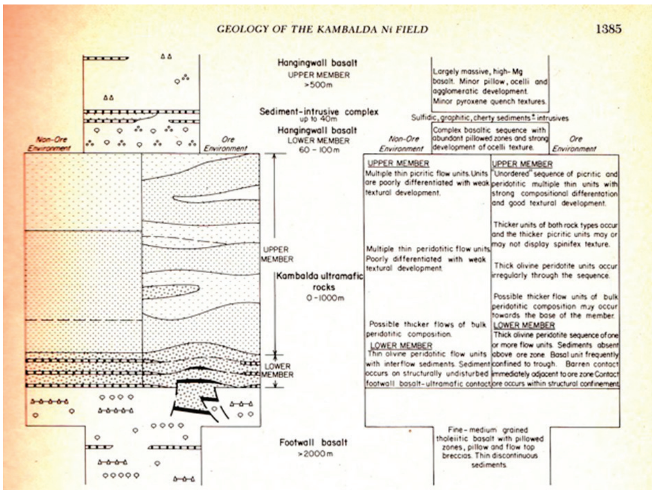

Figure 5. Stratigraphic column of the Kambalda sequence at the Kambalda Dome synthesising the understanding of the ore and non-ore environments as in the early 1980's (Gresham and Loftus-Hills, 1981).

by academics at universities and other research facilities but perhaps more importantly by the geologists who have worked on and developed an intimate knowledge of the deposits. WMC and the geologists who worked on the deposits at Kambalda from their discovery in 1966 until they were sold off to various third parties early in the 21st century made a major contribution to the evolving understanding of the model through a number of different avenues:

- The establishment of the position of Research Geologist and a research laboratory early in the mining history at Kambalda and the maintenance of this position and facility during difficult financial conditions.
- The support offered to employees to take leave and pursue studies on specific aspects of the geology of the deposits at recognised universities.
- Close communication with, and support of, external researchers
- The development and refinement of a geological legend that "saw through" the alteration processes that had affected the ultramafic rocks.
- The development of a quantitative XRD facility that allowed mine and exploration geologists to accurately define the mineralogy and magnesium content of the ultramafic rocks.
- Systematic and detailed mapping of all mine openings and compilation onto mine plans and sections.
- Systematic and detailed logging of all surface and underground drill core.
- Through this mapping and logging, the development of a 3-dimensional understanding of the orebodies and ore environment.

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Biography

JEFFREY GRESHAM has over 40 years experience in exploration, mining and corporate functions both in Australia and overseas. During a career spanning 19 years with WMC he held a number of senior corporate and technical positions, most notably Chief Geologist of the Kambalda Nickel Operations between 1981 and 1985 and Executive Vice President Exploration for WMC's Canadian subsidiary Westminster Canada Ltd between 1988 and 1993. He was subsequently Managing Director of Wiluna Mines Ltd and General Manager Exploration at Homestake Gold of Australia Ltd. Since 2001 he has been a consultant and director of various public companies.

New Technology Transforms Geologists

TIM GRIFFIN[1], STEPHEN BANDY and DAVID HOWARD

Introduction

The 1980s saw the beginning of a paradigm shift in the way regional field geological mapping was undertaken and presented to the resources sector by the Geological Survey of Western Australia (GSWA). A raft of new technologies changed the approach to field geology, and resulted in a major change in our understanding of the geological evolution and mineralization of the Archean granite-greenstones of the Yilgarn over the next two decades, setting the path for the 21st century. The following discussion focuses on activities of GSWA in the Eastern Goldfields. Here, new regional geological maps were overdue because the existing geological mapping, such as for the Widgiemooltha 1:250 000 scale sheet that covers the massive nickel deposits at Kambalda and elsewhere, did not recognize ultramafic komatiite lavas that host the nickel mineralization. Additionally, new mapping and geological interpretations were available from the intensive detailed mapping by nickel and base metals explorers in the 1970s.

Field Tools

The basic tools for field mapping, consisting of black-and-white stereo aerial photograph pairs, a hand stereoscope, compass, and paper topographic and geological maps would be rapidly displaced as we took full advantage of satellite imagery, airborne geophysics, computer technologies that provided ready access to colour images, accurate rectification of images, enhanced imagery, GPS to accurately locate information, digital photography, and digital notebooks that synchronized new geological observations directly with map-making databases.

Satellite images from Landsat were becoming commonplace, supported by an Australian Landsat receiving station and significant research in satellite image processing at the beginning of the 1980s. This followed the first Australian Landsat conference in 1979 and the establishment of the Australian Liaison Committee on Remote Sensing by Satellite.

Getting into the field to see the rocks and the rock relationships remains fundamental but, by the 1990s, we were achieving a far more effective and richer outcome that was starting to take full advantage of the new technologies and new information they provided.

Airborne Geophysics

The introduction of detailed airborne geophysical data (magnetics and radiometrics) provided unimaginable benefits in the Eastern Goldfields where the poor outcrop and extensive cover obscured relationships and limited our capacity to correlate greenstone units. The impact of airborne geophysics, beginning in GSWA in 1984 with access to an area of about twelve 1:100,000 map sheets of 200metre line-spaced data, was a major advance for regional field mapping, even though the first material we had to work with was monochrome contour plots. In 1990, GSWA was able to attract Federal support to collect data under contract, marking the start of a large, although sometimes sporadic, airborne geophysical acquisition program for Western Australia. The use of computer technology to process digital geophysical data in GSWA in 1993 coincided with advances in data processing being developed to display, understand and view Landsat data. The presence of magnetite in many metamorphosed ultramafic lavas in the Yilgarn made these units stand out so that they were mappable on aeromagnetic images. Features such as faults and folds, as well as the internal structure of the large granite batholiths that separate the greenstone belts were readily apparent.

Colour and Rectified Images

Advances in the use of colour by applying computer and related technologies to traditional photography provided massive benefits that were also critical to displaying Landsat and airborne geophysical interpretations as maps. In seems odd now; however, in the early 1980s, people across all disciplines requested coloured photographic images of Landsat 95% of the time compared to requesting digital data, simply because they did not have the technology to utilize digital data, and these images were not rectified.

Throughout the 1980s and 1990s, vast improvements were made in the capacity to interpret and display the digital data

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from multispectral and geophysical images. User-friendly GIS software meant that physical plots were replaced by images on computer screens where it is possible to match scales, and overlay and work with many layers of information in real time. This represented a major change from the use of a pantograph or costly standard photography, and later, photocopy machines, initially with significant distortion, to change scales of maps.

Remapping

For GSWA, the early 1980s saw the completion of the first pass of 1:250,000 scale geological maps and work had begun on second editions, mainly in areas where the first edition was very cursory or there was significant new information and interest from exploration companies, particularly in the Yilgarn. This revision process saw the introduction of more detailed 1:100,000 scale regional geological sheets as part of a systematic geological remapping program in recognition of the new data collected by companies, access to satellite imagery, airborne geophysical imagery, coloured aerial photography and computers. Computers enabled accurate rectification of regional spatial datasets as high-quality maps that could be used to identify and accurately locate geological features to be checked in the field. These processed data and maps enabled geologists to look through the cover and see the continuity of rocks units that had been identified at the surface or in drill holes, including the plethora of shallow RAB holes.

Geochemistry

Advances in geochemical analytical techniques were also game changing. Wet chemistry had given way to techniques such as Atomic Absorption Spectroscopy and X-ray Fluorescence. These were to become automated and many new analytical technologies added, including those that provided accurate trace element data, such as induced-coupled plasma (ICP) spectrometry. The abundance of geochemical information required the field geologist to develop a range of new skills in understanding the importance and capacity to analyse geochemical data, working with ratios, new types of graphs and isotopes.

Geochronology

In terms of unravelling the Precambrian geology in Western Australia, the most important advance was the development and acquisition of a SHRIMP (sensitive high-resolution ion microprobe) at Curtin University in 1994 that allowed for the accurate dating of rocks using the mineral zircon. Up until then there was no reliable way of dating the abundant Archean rocks in Western Australia. GSWA played a major role in securing Western Australian Government funding to support the purchase of the SHRIMP. Previously geologists were reliant on the Rb/Sr technique that largely recorded metamorphic ages that are open to much interpretation. Zircon dating rapidly advanced to the situation where the complex evolution of an individual zircon crystal could provide information on partial melting and metamorphic events.

Crustal Evolution

Trace-element and isotope geochemistry was also providing information on crustal evolution, enabling geologists to start to understand the evolution of the igneous rocks involving mantle extraction and multiple partial melting events.

1:100,000 Mapping

1:100 000 scale geological maps became the remapping standard for GSWA. By 2000 26 sheets had been completed in the Yilgarn, and 40 across Western Australia. In 2015 there are 241 1:100 000 scale geological map sheet areas now remapped across Western Australia.

Regolith Mapping

As new technologies were being applied to the basement geology, their application also resulted in significant advances in regolith mapping. This led to a much higher level of understanding in both the nature and evolution of the regolith which is a repository of great mineral wealth, and also, importantly, what it can ‘tell’ us about hidden mineralization.

The early radiometric images presented an amazing new insight into the spread and composition of the drainage systems across the Yilgarn. Regolith mapping transitioned rapidly from drawing simple boundaries interpreted from aerial photographs to mapping landforms using digital terrain models. Clay and iron oxide minerals mapping from processed multispectral imagery developed rapidly in the 2000s.

Map Making

Map-making processes in GSWA changed dramatically in 1989 from traditional pens, scribing tools and mark-up text to using computers and hand digitizing, and production of negatives for each colour plate for the printing press using computers. The Cheriton’s Find 1:100,000 scale geology sheet, south of Southern Cross, led the way in 1991. By 1995 reliance on a printed map from a printing press was history because excellent quality could be produced directly from a computer. Inkjet printers provide large, high-quality, full-colour printing at the scale of choice.

Perhaps the biggest initiative and challenge was to get all the geological information for making maps into structured databases that could be searched spatially. This allowed GSWA to generate maps quickly and efficiently, rather than the up to 10 years it had taken in the past to go from field work to the published map. The published explanatory notes were no longer the only account of the geology for a particular map sheet area. CDs, flash drives and data packages allowed us to distribute a much more comprehensive and enriched account of the geology and mineralization to accompany regional geological maps. The first CD of this type was for the Kalgoorlie 1:250,000 geology sheet in 1994. The presentation of information as digital packages and not just a map and explanatory notes has allowed us to include geochemical, geochronological and geophysical data as well as multiple images of the geophysics and Landsat data. This information, along with detailed interpretations that can also include evidence from deep seismic profiling provides a comprehensive, integrated package of geological and mineralization information for GSWA geological maps. By 2001, web based systems allowed a seamless view of large amounts of geological and related information to be available on demand via GeoVIEW.WA. A major change in approach was to produce the surface outcrop map by overlaying the regolith map on the interpreted basement geology map.

Our map production team was at the same time improving the materials we took into the field to make life easier for both the mappers and the cartographers back in the office. The introduction of GPS as a field tool was a massive change from the old way of recording sites by pricking the aerial photographs with a pin and writing the field number on the back. GSWA discovered how inaccurate the existing topographic mapping was in some areas of Western Australia. Geology seemed to be the one profession that was concerned about this shortcoming. GSWA commissioned a topographic remapping program, costing over $400,000, using differential GPS and satellite imagery to correct features on old maps that were up to 400 metres displaced based on the map grid versus the GPS location.

The GSWA cartographic team were now able to provide a range of composite field maps from rectified images and point location data from company reports. Information, including topographic maps, satellite imagery, geophysical imagery, old geology maps, sample sites and drill hole locations, etc., has led to more targeted field programs focussed on areas of critical geological interest or limited surface information. The layers of spatial information are available to be added, merged, and made semi-transparent on portable field computer with internal GPS capability that shows your location in real time, allowing new information to be added accurately and immediately, something we now take for granted.

Plate Tectonics and Terrane Mapping

Even though it was well recognized that there are characteristics that distinguish the granite-greenstones of the Yilgarn from modern tectonic environments, much attention has been given to the relevance of plate tectonic processes in the Archean. This has been a major area of debate in academic journals and at meetings such as the decennial Archean Symposia that are hosted in Perth. These discussions have great relevance to understanding the formation and distribution of mineral deposits in Archean terrains.

The Terrane theory promoted largely by North American geologists had a major impact on regional geological mapping, particularly on understanding stratigraphic sequences and nomenclature for the Yilgarn. Correlations across faults and areas of no outcrop that are possible terrane boundaries rely on the observational data being used in concert with the accumulating body of high-quality geochemical and geochronological data (Figure 1, Swager and Griffin, 1990).

Deep Seismic Profiles

Unravelling the deformation history and the role of thin-skin tectonics and the identification of repeated sequences through thrusting became a challenging issue, largely to separate the 'bandwagon' approach from what could be actually demonstrated. Geophysics provided support for these models in some areas, and the deep seismic traverses that had been a breakthrough in Canada provided great insight. The identification of both flat-lying and deep, mantle-penetrating crustal structures in the eastern Yilgarn were first published in 1991 based on seismic traverses across the Eastern Goldfields. These data also indicated that the granite intrusions and even batholiths could be relatively thin units, again providing a challenge to our traditional thinking.

Mineralization

The theories around mineralization also changed dramatically with the greater amount of robust data and new geological theories. Great benefit also came from the exchange of ideas with others working in similar rocks of a similar age, for example the Canadians and South Africans, in forums such as the Archean Symposia, but each of these ancient terrains has its own idiosyncrasies.

Risk

There has been a major shift in managing risk where employers must now demonstrate that all field work risks are minimized. We have moved from two-way radios and party lines with limited frequencies to satellite phones and personal EPIRBs. No longer can a geologist disappear into the outback for four or five weeks by themselves with no formal training or assessment of capacity to navigate and handle a 4x4 other than an orientation trip with a supervisor.

Conclusion

Being a field geologist changed dramatically in the two decades from 1980 to 2000 when field and interpretation skills had to broaden to embrace a wide range of new techniques and knowledge. The amount of information that has to be processed has expanded beyond what might have been thought possible. Fortunately much of the routine searching, data processing and analysis, including 3D modelling, can be done rapidly with computers.

GSWA has addressed the massive changes by recruiting highly skilled new staff, commonly PhD geology graduates and also BSc and MSc cartography graduates. GSWA staff are constantly presented with changes and challenges in regional field geology and map-making processes. We had to dramatically change the way we did our business in the two decades from 1980 to 2000, and this change is on-going.

Biographies

DR TIM GRIFFIN is the Deputy Director General – Approvals and Compliance, at Department of Mines and Petroleum in Western Australia.

Tim has over 15 years' experience in senior management roles relating to the minerals and energy sector. He worked as a geologist, primarily in field mapping in Papua New Guinea and Western Australia, prior to taking on the role as the Executive Director, Geological Survey of Western Australia in 2000 which he held for 10 years. Tim began his career in Western Australia in 1980 based in Kalgoorlie mapping the granite-greenstones of the Eastern Yilgarn. He also mapped extensively in the Kimberley before returning to the northern Eastern Goldfields prior to taking charge of the GSWA field mapping program.

Since being appointed to the role of Deputy Director General in May 2010, Tim has continued a strong focus on innovation and reform. These recent reforms have been on improving efficiencies by using electronic systems to speed up the submission and assessment of applications for approval to develop resource projects. The reforms have also facilitated higher levels of compliance to ensure environmental values are protected.

STEPHEN BANDY is the General Manager, Geoscience Information for the Geological Survey of Western Australia, a division in Department of Mines and Petroleum in Western Australia. Stephen has 40 years experience in cartography, with the last 25 years engaged in developing and implementing corporate wide GIS systems and responsibility for the management, use and integration of spatial technologies, and the on-going and planned growth of the spatial services within the Department.

A major focus in recent years has been finding new, innovative ways to deliver geoscience and resource information, including the management of major projects to deliver integrated spatial services at an enterprise level and the use of interoperability to disseminate geoscience information via web services.

DAVID HOWARD is Chief Geophysicist in the Mapping Branch of the Geological Survey of Western Australia responsible for regional magnetic, radiometric, gravity and electromagnetic data acquisition and delivery. His career in geophysical mapping and multi-commodity mineral exploration has included technical and general management roles in both public and private sector organisations in Europe, South America, Africa and Australia.

The Perfect Storm: A Holistic Overview

DAVID I. GROVES[1]

1950-1999 was, overall, a positive period in world history from a Western perspective. There was post-war euphoria and rebuilding, and strong leadership from politicians such as President John Kennedy: most of us still remember where we were on the day he was shot. The space race was on and the spacewalk was inspirational. There was rapid development of new technologies, and a cultural revolution to embrace. The News was not a 24-hour litany of gloom and doom.

Australia was still "the lucky country", continuing to preserve its positive competitive Aussie spirit whilst assimilating European migration. There was a re-birth of entrepreneurs who were not risk-averse. Litigation and "shrinks" were things suffered by people in the USA, and common-sense was our safety net. We excelled at tennis and cricket, and won the Americas Cup from the USA with Australia II and its winged-keel Aussie ingenuity. All this inspired a "go-get-it" attitude among Australians, including explorationists. In WA, Sir Charles Court was a giant in terms of promoting mining and developing infrastructure that aided the development of the minerals industry.

Education was structured, discipline was in place, and teachers generally had a vocation and were respected in the community. All students destined for tertiary studies understood the basics of the "three Rs" and only passed if they gained a grade of greater than 50%. They were literate enough to move to universities which were places of excellence in teaching and research, not businesses serving customers. Second-rate universities were institutions in the USA. Entrance to geology courses required science prerequisites, the degrees were structured, fieldwork was compulsory, and field-based Honours degrees were the "jewel in the crown". Most geology graduates had a vocation and were prepared for the workforce in country towns or remote locations.

Technology advanced rapidly. The period saw the birth of modern geophysics and rapid geochemical techniques that could be applied in exploration. Technology enabled, not replaced, brainpower. Geologists were still superior observers. There were exceptional explorers (e.g., Roy Woodall and Haddon King) using the new technologies and blending quality science with pragmatic exploration. In parallel, there were superior intuitive prospectors (e.g., Mark Creasy and Lang Hancock) defining exploration frontiers. Wealth was created by discovery, not just acquisition. A number of juniors became mid-tier companies and a few became majors of that time. There was mentorship in exploration offices in country towns and some company geologists were supported through PhD or MSc degrees. Kambalda was consistently "A Nursery of Champions" throughout both the nickel and gold booms. There were no FIFOs, so geology exceeded safety in the training hierarchy.

There was excellent pre-competitive geoscientific support. Under Joe Lord, GSWA mapped the State. BMR provided regional geophysical datasets that aided geological understanding in the Yilgarn and which industry used to help discover deposits such as Olympic Dam. CSIRO was the world leader in regolith research, UWA and Curtin both had excellent research programs in the Yilgarn, and pragmatic Key Centres around Australia provided exploration-relevant teaching. AMIRA and WAMPRI/MERIWA provided vital support to link academic research to industry needs in the period. This led to an excellent understanding of the geology, regolith and gold and nickel deposits in the Yilgarn by the late-1980s to early 1990s.

Perhaps I could be accused of being an old curmudgeon looking at the past through rose-tinted glasses. However, I believe we were fortunate to experience the "Golden Age" of universities, Government geological surveys and mineral exploration at a time of Yilgarn terrane immaturity and of life less restricted by excessive bureaucracy, political correctness and Governmental red-tape. It bred a generation of exceptionally successful explorers, turning juniors into mid-tiers, or even majors, through discovery. It helped to transform WA from a sleepy backwater on the west coast to THE mining centre of Australia, with over an order of magnitude increase in population in half a century. It was indeed a "Perfect Storm".

Can it be repeated? The lack of inspiring political leadership, the total failure of the current democratic parliamentary process to define a vision for Australia and implement it, increasing red-tape and delays in decision making, a serious

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decline in education standards, particularly as they apply to the practical sciences, and an increasingly less self-dependant Aussie attitude suggest it will be difficult to rise like the phoenix from the ashes of the current downturn. However, WA needs such success through inspired exploration undercover in increasingly mature terranes like the Yilgarn.

Positive steps in pre-university education for future geologists by Earth Science WA (ESWA) and the Exploration Incentive Scheme, managed by the Department of Mines and Petroleum (DMP), are steps in the right direction. Could this Yilgarn Retrospective meeting inspire a think-tank to investigate other initiatives that might further reinvigorate professional training and exploration while all the greybeards still have the mental capacity to contribute, or are the problems of raising exploration funding insurmountable in this current risk-averse investment community?

Biography

DAVID GROVES received a BSc Honours (1st class) and PhD from the University of Tasmania. He joined the University of Western Australia (UWA) in 1972 as Lecturer, and became full Professor and Founder and Director of the Key Centre for Strategic Mineral Deposits (later Centre for Global Metallogeny) in 1987. His main expertise has been in orogenic gold deposits globally and temporal evolution of mineral deposits. He has been President of the Geological Society of Australia, SEG and SGA, and has been awarded 11 medals for his research, including both the Gold Medals of SEG and SGA for lifetime contributions to economic geology, and the Geological Association of Canada Medal. Since retirement, he has been awarded an honorary DSc. from UWA and consulted to the gold exploration industry and investment groups on all continents, mainly for Canadian companies in Africa and Brazil. This has resulted in one significant discovery and several on-going technical successes. He has also presented workshops on orogenic gold in Australia, Canada, New Zealand, UK, and also in several African countries, and on geological aspects of the business of exploration in Canada and the UK to brokers and investors.

A Different Perspective on the WA Mining Boom

JACK A. HALLBERG[1]

The burst of mineral exploration, development and geological documentation that occurred in Western Australia in the latter half of the twentieth century is well known. To put this period into a 'world' context, I will briefly look at events and attitudes that shaped the direction of exploration and development in the USA, USSR and Western Australia at this time.

In general, the US government and most large American mining companies were dominated by conservatism and isolationism through much of the 20th century. The laws governing land acquisition and tenure, mining development, and environmental matters vary from state to state, and because most date back to the mid- to late 1800's or before, they are often confusing and/or contradictory. Data reporting requirements also vary, and in some states are largely non-existent. The above conditions tended to stifle development and regional exploration. New ideas were slow to be accepted, and land tenure, environmental matters, and exploration near known deposits were more pressing than grass-roots exploration. Air photos were not used for mapping in the USA, geological information instead being compiled on topographic maps and tied into the PLSS (Public Land Survey System) by pace and compass. Base map data on many geological maps is still referenced to surveys conducted in the 1800s. As can be imagined with no GPS for aid, more time was often spent navigating than looking at rocks. Mapping was slow, often inaccurate, and individual sheets were often mapped piecemeal with no regional plan in mind.

The major phase of Russian exploration occurred in the latter half of the 19th century. Led by explorers such as Nikolai Przewalski (1839-1888) much of central and eastern Asia was explored, and trade routes defined and established. After 50 years of conflicts, 1950 arrived in the USSR during a period of relative quiet, although the prospects of a prolonged cold war with the USA loomed. With this motivation and a presumed need for minerals and fossil fuels, and having a source of manpower (Russian army), systematic sampling and mapping of the huge Russian federation began. In their search for minerals the Russians adopted whole-heartedly the work of V. M. Goldschmidt (1848-1947) a Norwegian mineralogist and chemist who suggested that selected suites of pathfinder trace elements could be used to locate selected types of mineral deposits. Conscripting local geologists when possible, geological sampling and mapping from Eastern Europe to central Asia located, in a relatively short period of time, many fossil fuel and mineral deposits. Despite exploration successes, inherent bureaucracy and, in some instances, corruption made exploitation of new resources less than ideal.

Within Australia (and in fact most Commonwealth countries) geological surveys were established based on the English background of regional mapping and meticulous documentation. These surveys were generally staffed with dedicated professionals supported by various analytical facilities. In the period 1895-1915 workers at the Geological Survey of Western Australia developed an excellent understanding of regional geology and associated mineralization incorporating petrographic and geochemical data. Although Survey activities were slowed by the two world wars, mining companies were still actively searching for new resources using new and often innovative techniques. During the 1950's and 1960's pathfinder element geochemistry became more practical with the development of more accurate and more rapid analytical techniques (AAS, XRD); advances in geophysical tools were also being made. Australian exploration companies and service providers were less conservative than their overseas counterparts and readily embraced new technology and ideas.

I had never seen an air photo on arrival in Australia in 1967, had never considered looking at things regionally, and had never encountered such a wealth of support data. I soon realized that regional mapping was my future direction. After some years of using available aerial photography I decided on a map scale of 1:25 000 as being most useful. Such a scale offered enough detail for understanding but could easily be presented at 1:50 000 and 1:100 000 scales. I have mapped 350 standard 1: 25 000 map sheets in Western Australia, all mapping supported by petrology and analytical data, and most by the inclusion of magnetic susceptibility measurements (Figure 1).

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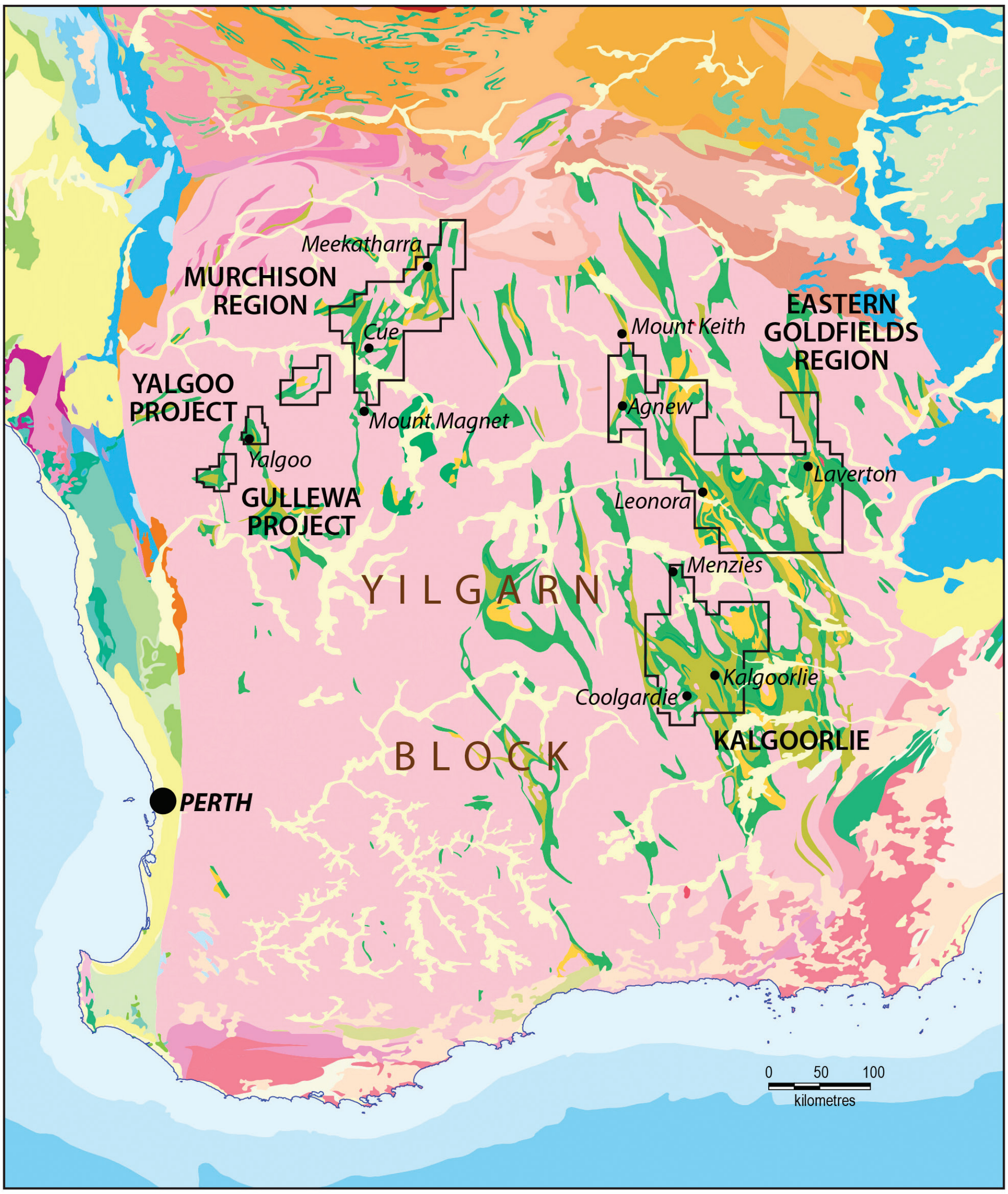

Figure 1. J A Halberg 1:25,000 geological map coverage of the Yilgarn Block

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Biography

JACK HALLBERG has 7 years' experience carrying out mapping and research in the USA. He has been employed by the Arkansas Geological Survey, the Connecticut Geological Survey, the USGS and the US government. Since 1967 the author has resided in Western Australia where he has published over 50 papers and 350 standard 1:25 000 map sheets concerning Western Australian geology.

From a Mile to a Chain: The Story of Aeromagnetics in the Yilgarn

DAVE ISLES and PAT CUNNEEN[1]

Overview

Aeromagnetic surveys with 1-mile line spacing opened the door to continuous solid geological mapping in the Yilgarn in the mid 1950s. Prospect scale gold exploration in the region is today supported by airborne surveys with line spacings as low as 20m (20m=21.87yards ~ 1 chain!). The transition from broad-scale to ultra-detailed coverage has been based on the extraordinary geological content delivered by aeromagnetic surveys and their critical contribution to all forms of exploration in the Yilgarn. We outline the main phases of application of aeromagnetics in the region and highlight the turning points where 'breakthroughs' lead to heightened interest in, enthusiasm for and successful application of this most versatile geophysical tool.

Phases of Aeromagnetic Application

1948 saw the first aeromagnetic survey in the Yilgarn when contractor Oscar Weiss flew in the Southern Cross 'BIF belt' for Zinc Corporation and WMC. This led to the Australian Government Bureau of Mineral Resources (BMR) acquiring Weiss's DC3 aircraft and installing its own instrumentation.

BMR 1-mile coverage

The Yilgarn was soon chosen by BMR to assess its new airborne systems. The Southern Cross 1:250 000 sheet was flown in 1957 followed by Jackson, Barlee and Kalgoorlie sheets in 1958. The line spacing of 1 mile (~1600m) and flying height of 500 feet (~150m) was adopted as the prevailing standard.

The presence of 'jaspilites' drove the choice of initial BMR survey areas, but there was an expectation that the aeromagnetic data would differentiate greenstone belts from granitic regions and define geological structure under cover (Spence, 1958). They were not disappointed!

The 1-mile coverage continued as part of BMR's Australia-wide programme and the main goldfields were completed by 1970. The paper contour maps produced 'manually' had a major impact on the late 1960s – early 1970s nickel boom by mapping the distribution of the ultramafic-bearing greenstone belts. 1-mile coverage of the Yilgarn was completed in 1981.

Detailed company surveys

Exploration companies flew local surveys with lines spaced 200-500m during the nickel boom and these played a crucial role in guiding exploration (Gemuts and Theron, 1975). Survey activity increased slowly until the resurgence of gold exploration in the late 1970s, when digital acquisition and processing became routine and companies began to fly larger and tighter surveys.

The Aerodata multiclient adventure

1983 brought a step change in the application of aeromagnetics in the Yilgarn which soon had an impact worldwide. Local contractor Aerodata initiated 'spec' surveys in the Yilgarn goldfields - non-exclusive surveys over tightly held exploration tenure that allowed explorers to purchase 'tailored' coverage at considerably less than the contract acquisition cost. The uptake was immediate and strong. The Menzies-Norseman belt was completed in 1986 and coverage in the Leonora-Laverton and Murchison regions commenced. The goldfields aeromagnetic 'recipe' was 200m line spacing flown at 60m height. The basic product was 1:25 000 scale, black line TMI contour maps but Aerodata's early investment in image processing hardware and expertise in 1986 had the contour products supplemented by stunning imagery—again the geological community flocked to take advantage of this completely new and detailed view of the goldfields geology.

What were geologists seeing that had not been seen before? The continuity of 200m data over very large areas yielded local scale structural and lithological detail as well as district and semi-regional (1:100 000-1:250 000) scale context that was 'awesome'. Earlier clumsy and coarse attempts at delineating the Archaean geology and structure gave way to incisive interpretations that could be closely related to on-ground observations. The advances in structural thinking that happened at that time gained as much from the aeromagnetics as from the detailed observations at outcrop scale.

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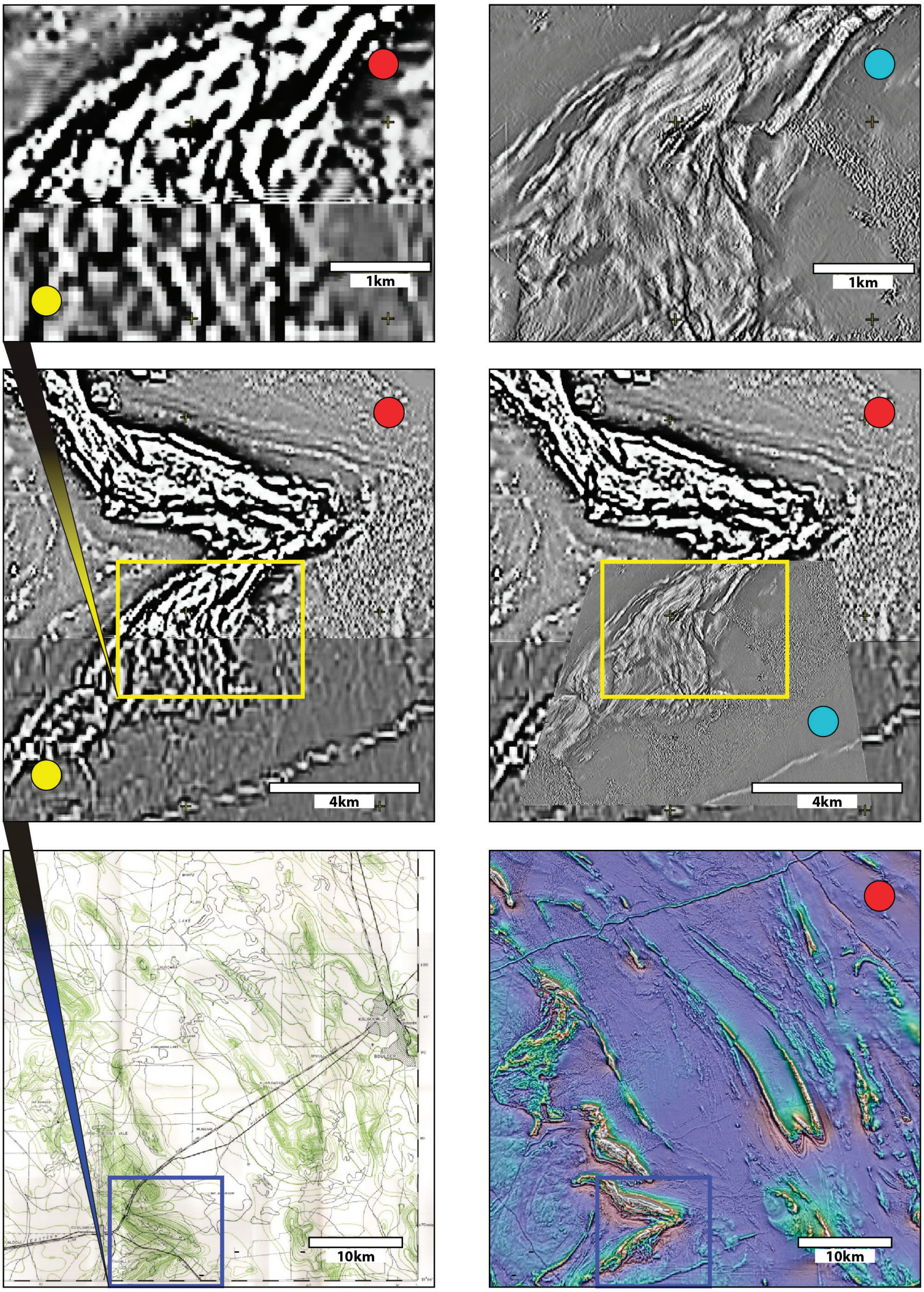

Aeromagnetic Imagery from the Coolgardie-Kalgoorlie Area

Contour Map - BMR '1-mile' 1958
Aerodata 200m 1983
NHG 20m 1998
GSWA 'EIS' 100m 2014

Figure 1. Images of aeromagnetic survey data flown at 20m, 100m, 200m (all RTP derivative images) and 1 mile line spacing (TMI contours) in the Coolgardie area. The 20m data is presented courtesy of Metals X.

The National Geoscience Mapping Accord (NGMA)

In 1989, the BMR and the State Geological Surveys formed the NGMA. At this time the BMR's 1:250 000 scale geological mapping was complete, as was the '1-mile' aeromagnetic coverage and the direction of government mapping and acquisition of 'pre-competitive' data was to be determined. The states had begun 1:100 000 scale mapping programs and acquisition of semi-detailed (400-500m spacing) airborne magnetic/radiometric surveys in key provinces. The NGMA proved to be a giant leap forward in Australian geoscience.

For the Yilgarn, like many other Australian mineral provinces, this heralded the acquisition of 400m-spaced aeromagnetics/radiometrics along with programs of 1:100 000 scale geological mapping. At that time commercially available multiclient data covered the prime mineralised belts and the NGMA flying aimed to extend the coverage to complete 1:100 000 sheet areas and particularly the peripheral, remote or unfashionable areas. The data was initially distributed on a 'cost recovery' basis, but this changed once the NGMA flying commenced in South Australia and that State decreed that all data would be distributed free of charge. One-by-one, the States and AGSO (formerly BMR and subsequently GA) followed SA in waiving charges for the airborne data such that by the mid 1990s there was an Australia-wide 'feeding frenzy' by explorers on high quality aeromagnetics. By the late 1990s, imagery of the entire Yilgarn largely based on 400m and 200m data was widely available.

An important outcome of the NGMA was 'GADDS', a central store of all substantial public geophysical data in Australia enabling free download of whole surveys or tailored sections in raw or processed form.

Ultra detailed surveys

In 1994, UTS Geophysics offered a new aeromagnetic product - helicopter-borne magnetometry with a stinger-mounted sensor flown with 20m line spacing at 20m height. The uptake of this 'airborne ground magnetics' was not immediately strong, but it gained momentum in parallel with the 1993-1996 gold 'mini-boom'. Once again there was a step change in the information content from aeromagnetics. Working imagery could now be produced at 'mine scale' – 1:2 000 scale was achievable and coarser scales, 1:5 000 and 1:10 000 yielded a stunning level of geological detail. The addition of the ultra-detailed data to the regional picture already established by the 200m Aerodata multiclient coverage greatly advanced the structural thinking in gold exploration.

MAGIX

GSWA established the MAGIX system in the 1990s as an index of company and government airborne surveys. It provides survey outlines and data specifications as well as availability. At this time GSWA also introduced a 'sunset' scheme whereby company airborne surveys would normally lose confidentiality after 5 years. Numerous ultra-detailed and often extensive aeromagnetic surveys are now available through this system in the Yilgarn goldfields.

EIS

The Western Australian Exploration Incentive Scheme (EIS) followed similar initiatives in WA and other states whereby pre-competitive data was acquired and subsidies for drill testing strategic exploration targets were available. A very large program of 100m-spaced aeromagnetic/radiometric surveying was initiated in the Yilgarn Goldfields as part of the EIS in 2009, and this program is largely complete.

Figure 1 shows the EIS data in the Coolgardie-Kalgoorlie district, along with the 1958 BMR 1-mile data, the 1983 Aerodata 200m multiclient data and ultra-detailed (20m) data flown for NewHampton Goldfields in 1997. A comprehensive geological interpretation of this area can be found in Tripp (2014).

Technology Step Changes

The early 1970s saw the change from paper chart recording and entirely manual compilation of aeromagnetic to digital recording and processing. This not only reduced the turnaround time and cost of surveys but facilitated the use of sophisticated filtering and interpretation algorithms. Its effect was to expand the scope of many planned surveys.

Image processing appeared in the early 1980s and heralded a new era in data visualisation. Instead of the laborious process of reading the geology from contour maps and stacked profiles, explorers saw the geology 'leaping off the page'. This was the turning point where the geological community realised that it should take control of the aeromagnetic interpretation process and leave the geophysicists to concentrate on acquisition and processing. It was arguably the most important advance in leveraging 'exploration action' from aeromagnetic data.

Navigation by GPS was established in the industry by the mid-1990s, replacing hybrid/radio positioning and aerial photo based visual position fixing. Although largely transparent to the end user, this development raised the precision and reliability of positioning remarkably, and more importantly caused another quantum change in survey efficiency and cost.

Magnetometer developments saw data resolution reduce from 1-2nT to 0.1-0.2nT over the 50 years, but this had minimal impact in the Yilgarn where magnetic signals from all sources are generally substantial.

For the Yilgarn, image processing trumped all other developments, but equally importantly, the efficiencies of digital recording and GPS positioning enabled extensive surveys to be planned and executed at extraordinarily low cost.

The Current Yilgarn Aeromagnetic Data Base

Freely available 400m- and in parts 200m-spaced data sets cover the greenstone belts and most of the remaining sub-crop areas of the Yilgarn. The new 100m (at 50m height) EIS flying now covers very large areas of 'mature' gold (and nickel) exploration territory. Ultra-detailed (20m-50m line spacing) surveys exist in many key areas either free or available commercially at minimal cost. The 50m-spaced survey flown in the St Ives district by WMC in the 1990s is a good example. Exploration in this challenging salt lake environment continues to be extraordinarily successful and the use of ultra-detailed aeromagnetics has played a major role (Miller et al., 2010). The Aerodata coverage remains an important resource in some 'outlying' areas.

GSWA updates the best available State aeromagnetic data into grid and image form regularly. For the Yilgarn, the best current resources are the State 40m grid and the 'Goldfields' 20m grid, the latter being the compilation of the EIS data and appropriate company surveys. This makes WA the world leader in provision of high-resolution aeromagnetics to its exploration, mapping and research communities.

Interpretation - What have we 'done' with all of this aeromagnetic data?

The nickel boom yielded some noteworthy interpretations. The solid geology map of the Coolgardie-Norseman region by Gemuts and Theron (1975) used both BMR and company surveys. 1:1 000 000 solid geology compilations by Marston (1984) and Colville (1989) followed the comprehensive, Yilgarn-wide compilation done by Hunting Geology & Geophysics (~1982, unpublished). This was based mainly on the BMR 1:250 000 geological mapping and aeromagnetic maps. It was compiled as individual 1:250 000 solid geology sheets and merged into a 1:1 000 000 composite.

The 1980s gold boom brought a flood of detailed aeromagnetic surveys and it became apparent that the main requirement for aeromagnetic interpretation was a sound grasp of geology and structure rather than the 'physics' of this geophysical tool. The geological style of interpretation/ integration methodology was initiated by contractors such as Huntings, Southern Geoscience and Aerodata (e.g., Isles et al., 1989), the latter collaborating with Yilgarn mapper, Jack Hallberg to produce integrated solid geology maps in selected areas. GSWA geologists recognised the need for access to this data to assist their 1980s 1:100 000 scale mapping and such access was duly negotiated with Aerodata. This added great value to the mapping in the Menzies-Norseman Belt and culminated in the publication of a 1:250 000 solid geology/ structural interpretation of the broader Kalgoorlie-Kurnalpi region (Swager et al., 1995) which set the scene for future such compilations in Yilgarn. Since the late 1980s, solid geology and structure maps based as much on aeromagnetics as surface geology have become the norm.

As the NGMA evolved and the government 400m-spaced aeromagnetic coverage reached beyond the mainstream greenstone belts, broader scale compilations were done leading to the first digital solid geology map of the Yilgarn (Whitaker, 1992). At much the same time, an arrangement was struck between Aerodata and geological consultants Etheridge, Henley and Williams to jointly produce and market 1:100 000 scale interpretations of the Aerodata aeromagnetics. Thirty 1:100 000 sheet areas were produced and these solid geology maps included an expansive interpretation of not just structural style, but also deformation history (SRK, unpublished).

In order to address and assist the transition from 'geophysical' to 'geological' styles of interpretation, Aerodata, in 1988, formed a training course in aeromagnetics for geologists. This course is still presented and has had considerable impact on the utilisation of aeromagnetics in the Yilgarn. It is now published as an e-book (Isles and Rankin, 2013).

Outlook

The Yilgarn is a massive area containing prospective sections that are daunting in both scale and degree of hostility to explorers. To consider that most significant discoveries have been made in this highly fertile province would be to give more credit to historic exploration efforts than is arguably due.

Exploration will no doubt push on in the region and discoveries large, small, shallow and deep will occur. Aeromagnetic data should play an increasingly front-line role as the search space deepens and levels of structural detail contained in the aeromagnetic data expand. We predict that the shake down of the next 50 years of exploration in the Yilgarn will see geologists increasingly present geology based largely on aeromagnetics without reference to the geophysical technique, in much the same way as the role of aerial photography has been 'taken as read' for many years.

The growth in the utilisation and value of aeromagnetics in the past 50 years has been impressive. The state of currently available data is almost overwhelming and the scope for using the data to vector in on new discoveries remains huge.

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Biography

DAVE ISLES commenced his engagement with Yilgarn gold exploration in 1983 as a project geophysicist with BHP Minerals. From 1987 to 1993 he was involved with Aerodata's multiclient airborne survey program and formed an interpretation team within that group. From 1994 to 2000 he was a director of local gold producer HewHampton Goldfields. His current affiliations are with Southern Consultants and TGT Consulting, through which he offers training programs in aeromagnetic interpretation. He is a member of AIG, ASEG and SEG.

PAT CUNNEEN is a third generation explorer of the Yilgarn as both his father and grandfather were prospectors and small mine owners, specifically at Bulong and Mount Monger. He is one of the very few surviving alumni of Mt Monger Primary school. Pat is the founder of both Aerodata Holdings and World Geoscience an achievement for which he received the Society of Exploration Geophysicists Enterprise Award in 2002.

From Kambalda to the Rest of the World and Back: A History of Our Understanding of Komatiite-Associated Ni-Cu-(PGE) Deposits

C. M. LESHER[1]

Fe-Ni-Cu sulfide mineralization in what are now known as komatiites had been mined in the Abitibi Greenstone Belt in northern Ontario since the 1910s, equivalent deposits had been discovered in the Cape Smith Belt in northern Québec in the 1930s, and subvolcanic equivalents had been discovered in the Pechenga Belt in the Kola Peninsula in the 1910s and at Thompson in Manitoba in the 1950s. However, it was not until the discovery of the Kambalda deposits by Western Mining Corporation in the late 1960s that volcanic ultramafic-hosted deposits were recognized as being an entirely new class of magmatic Ni-Cu-PGE mineralization.

Most models for the generation of Ni-Cu-(PGE) deposits at that time involved closed magmatic systems and transport of sulfide droplets from the mantle or felsification of sulfide undersaturated mafic-ultramafic magmas. After detailed exploration and research at Kambalda in the late 1970s and early 1980s it was appreciated that the host rocks at Kambalda were distal lava conduits and only small parts of much larger systems, and that the ores formed by upstream melting of sulfide-bearing footwall rocks and upgrading of sulfide xenomelts during horizontal transport. Larger lower-grade deposits in the northern part of the Yilgarn were then understood to be subvolcanic equivalents. This provided a basis for using the geological-stratigraphic-volcanological characteristics of the ore-forming environments and the mineralogical-geochemical-isotopic consequences of these processes as a comprehensive multidisciplinary exploration footprint. Exportation of these models to deposits in Québec, Ontario, and Manitoba in the 1990s provided tools that significantly reduced exploration costs and increased discovery rates. In turn, these areas preserved even better evidence for thermomechanical erosion, showed that sulfides can be extracted from a wide range of wall rocks (including sulfidic cherts, sulfidic slates, sulfide-bearing volcanic rocks, VMS-style mineralization), and showed that the ore segregation profiles and therefore mechanisms of ore emplacement were often much more complex than at Kambalda. Extrapolations to other types of magmatic Ni-Cu-PGE deposits, including those hosted by rocks derived from picritic, komatiitic basaltic, and continental flood basaltic magmas, indicated that that they too formed in dynamic magma conduits, that even sulfates may generate ores if reductants are also present, and that even alkali picrites may be prospective. The latest contribution is work started in the mid-2000s on the deep crystal structure of the Yilgarn block, which indicated that the Kalgoorlie-Norseman belt is a long-lived crustal suture that guided the ascent of mantle-derived plumes. This nicely explains the association between plumes (needed to generate large, dynamic magmatic systems), rifting (needed to ensure rapid ascent to volcanic-subvolcanic levels), and continental margins (needed to generate S sources). And this, too, has broader applications, explaining for example the long-recognized but until then unexplained localization of plume-related magmatism and associated Ni-Cu-PGE deposits along craton margins in the Circum-Superior Belt and other parts of the world.

These advances – all based to one degree or another on work started at Kambalda, work done by people trained at Kambalda, or work influenced by models developed for Kambalda – have fundamentally and forever changed geological, genetic, and exploration models for magmatic Ni-Cu-(PGE) deposits.

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Biography

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Western Australia - So Boring Until Some Explorers Lit the Fuse in the 1960s.

RON MANNERS[1]

They say that history is like a second shadow to us. It always follows us around.

This is an appropriate thought to all of us whose lives were picked up and turned around by the remarkable events that occurred in Western Australia in the 1960s. These significant results came from a small bunch of dedicated explorationists who believed and practised their fine art during exploration's 'darkest hour'. Unlike today, these courageous explorationists were actually encouraged by far-sighted management.

This 'Yilgarn Retrospective' symposium will give many of us, who lived life to the full throughout this era, the opportunity to reflect on how everything changed, particularly in our State. Our lives, our livelihoods and our lifestyles were all transformed. Our 'Sleepy Hollow' became 'the centre of the universe' as fortunes were made and lost on a daily basis.

How fortunate we were to have lived through this trail-blazing era!

However, during this period there were many external events and changing economic policies that added leverage to our exploration activities, and for these helpful stimuli we should also be thankful.

There will be many stories swapped and recorded during the two days of the symposium, both on and off the podium. Perhaps Albert Einstein, toward the end of his life, may have had this remarkable exploration renaissance in mind when he coined the phrase; 'creativity is intelligence having fun'.

Perhaps the enthusiasm flowing from this two-day meeting will lead us to believe that we will see a similar resurgence again.

How will we handle it next time?

Biography

RON MANNERS is Founder and Chairman of the Mannkal Economic Education Foundation, and is Managing Director of the Mannwest Group. He is also Emeritus Chairman of the Australian Mining Hall of Fame Ltd, and a Fellow of both the Australasian Institute of Mining and Metallurgy, and the Australian Institute of Company Directors. His contributions to industry and Australia have been marked by several awards. In 2010 Ron was appointed to the Advisory Council for the Atlas Economic Research Foundation, Washington, DC.

Ron was born in Kalgoorlie, Western Australia, to a prominent local family. A fourth generation prospector, he studied electrical engineering at the Kalgoorlie School of Mines before he assumed management of the family mining/engineering business, W.G. Manners & Co., in 1955. This private company, which he has expanded and diversified and is now the Mannwest Group, has been operating continuously since 1895 (which is six years before Australia had a Constitution or a flag).

Between 1972 and 1995 Ron floated several publicly listed mining companies, one of which became Australia's third largest gold producer, before joining the board of a Canadian company with gold operations in Mexico, Brazil and Turkey. In addition to his mining interests, Ron established the Mannkal Economic Education Foundation in 1997. The Foundation has sponsored over 700 young students to internships and conferences in many countries, including Australia. He is a life member of the Mont Pelerin Society and is on the coordinating Committee for the Commonwealth Study Conference.

Ron is also the author and editor of five books: So I Headed West; Kanowna's Barrowman – James Balzano; Never a Dull Moment; Heroic Misadventures: Australia; Four Decades - Full Circle and Poems of Passion (A Prospector's Poetic Soul) - as well as numerous papers and addresses.

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Geochronology Research: From 4D Evolution to Revolution

NEAL J. McNAUGHTON[1]

The geological map is the foundation of mineral exploration. Improvements in the geological maps of the Yilgarn available to mineral explorers are essentially communicated via new generation maps produced by the Geological Survey of WA (GSWA), and a few specialist and respected mappers such as Jack Hallberg. Apart from more thorough field studies and new subsurface information, the most significant advances in understanding the bedrock geology of the Yilgarn has come from new geochronology and airborne/ground geophysical datasets, integrated with global advances in tectonics and metallogeny.

Geochronology is a subdiscipline of isotope research, which was started in WA with Peter Jeffery (UWA) and evolved through his "disciples", particularly John de Laeter, Bill Compston and Kevin Rosman. The application of isotope research to the Yilgarn was largely initiated by John de Laeter (Curtin), David Groves (UWA) and Alec Trendall (GSWA) in the mid-1970s. New staffing positions in the late 1970s and early 1980s at UWA (Mike Bickle, Hazel Chapman, Neal McNaughton) and Curtin (Bob Pidgeon) targeted "geochronology" to complement largely academic field and geochemical studies, and the link between the necessary analytical infrastructure (mostly at Curtin) and the geochronology applications (driven from UWA, Curtin and GSWA), was born via collaboration.

Independently, Bill Compston at ANU was leading the development of a new mass spectrometer, specifically designed for geochronology: the SHRIMP (Sensitive High Resolution Ion MicroProbe). By the early 1980s, zircon U/Pb geochronology by SHRIMP was about to revolutionise Archaean geochronology. At the same time, geochronology "robustness" was being better understood and the Sm-Nd isotopic technique was being developed and applied via postdoctoral appointments of Ian Fletcher (at Curtin) and from overseas by Malcolm McCulloch (now at UWA, but a former student of John de Laeter).

All geochronology research requires sophisticated and expensive equipment. The earlier collaboration between Curtin-UWA-GSWA, now embodied in the John de Laeter Centre, was pivotal in establishing new and updated geochronology facilities at Curtin, which ultimately led to the successful bid to purchase the first commercially produced SHRIMP in the early 1990s.

Thereafter, the demand from the three partners quickly outstripped available instrument time, and a second SHRIMP followed. Almost all of this SHRIMP work in the 1990s was geochronology, with the major component directed towards the Yilgarn. New specialist geochronology appointments (Peter Kinny, David Nelson, at Curtin, and Ian Fletcher, at GSWA) and many staff and research students at UWA and Curtin utilised SHRIMP and the other isotopic techniques to successfully add to our knowledge of the 4D evolution of the Yilgarn.

Importantly, the mushrooming of SHRIMP geochronology activity in the 1990s coincided with the heyday of the ARC Key Centre for Strategic Mineral Deposits at UWA, and brought a mineral deposit focus to much of the SHRIMP research at UWA. Together with Pb isotope tracer studies and geochronology (from the 1980s), important new advances in the understanding of the 4D development of the Yilgarn were made, and through the GSWA, were transferred to the new generation of maps available to mineral explorers.

Although not strictly within the 50-year focus of this meeting, the foundations established from the Curtin-UWA-GSWA collaboration that started with de Laeter-Groves-Trendall opened new research avenues in geochronology, including the development of REE-phosphate U/Pb geochronology of ore deposits, Re-Os geochronology of ore sulphides, diagenesis geochronology via xenotime, dating metamorphism with titanite ('sphene' to this audience) and rutile, and the whole research area of thermochronology using Ar-Ar and U-Th/He techniques. Geochronology for 4D evolution studies during 1950-1999 was the forerunner of the geochronology revolution, in which the relative timings of geological events derived from field/petrographic observations are tested, revised (if necessary) and quantified into an absolute time scale. The geochronology revolution has started, and Curtin-GSWA-UWA are driving it, with industry support and aspirations.

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Biography

NEAL McNAUGHTON has specialised in stable and radiogenic isotope research for over 35 years. For the last 30 years, this research was mostly related to metallogeny, particularly gold in the Yilgarn, and he has co-authored over 100 publications on gold deposits around the world, mostly in collaboration with students and colleagues at the former Key Centre for Strategic Mineral Deposits and Centre for Global Metallogeny at UWA. He is currently Research Professor at Curtin University and leads the research program on the "4D evolution of WA ore deposits", supported by industry, government and Curtin University.

From Research Breakthroughs to Discovery of 200 Moz of Gold

NEIL PHILLIPS[1] and EDUARD ESHUYS[2]

Success of Gold Exploration and then Production from the Yilgarn Craton

If Yilgarn gold production was monitored from 1950 until 1979, it would be easy to conclude that here was a sunset industry. If you were to propose an innovative exploration programme for Yilgarn gold during that period, someone would reject it with a simple statement that Yilgarn gold was *mature**. Numerous small and mid-scale operations had closed, either running out of ore or simply becoming unprofitable.

That gold in the Yilgarn craton suddenly became of interest from 1979 was helped greatly by a substantial rise in the gold price due to the second oil shock that year. Interestingly, Australia gained virtually no direct benefit from this record $800 per ounce (US 1979 dollars) price because Australia's annual gold production was negligible, just 19 t in 1979. Furthermore, Australia was in no position to bring operations into production quickly because it had few identified gold resources. The Economic Demonstrated Resource figure for the whole of Australia was only 220 tonnes of gold at the start of 1979; by comparison, that figure for the start of 2013 was 9900 t Au (Geoscience Australia, 2013) despite substantial production in the meantime.

The story of Yilgarn gold from 1979 has influenced gold exploration elsewhere in Australia and globally; and it was in the Yilgarn where some key scientific breakthroughs were made, and from where the bulk of discoveries and subsequent production have come. Every year since the Australian gold boom of the 1980s and 1990s, the major source of Australian gold production has been the Yilgarn craton.

The importance of the Australian gold boom from 1979 can be seen from production, resources and discovery figures for the following quarter of a century. In 25 years, and solely within the Yilgarn craton, production was 3116 tonnes, Economic Demonstrated Resources rose from 128 t to 3278 t, and therefore 6265 t Au were discovered in the Yilgarn (Phillips, 2004; Figure 1).

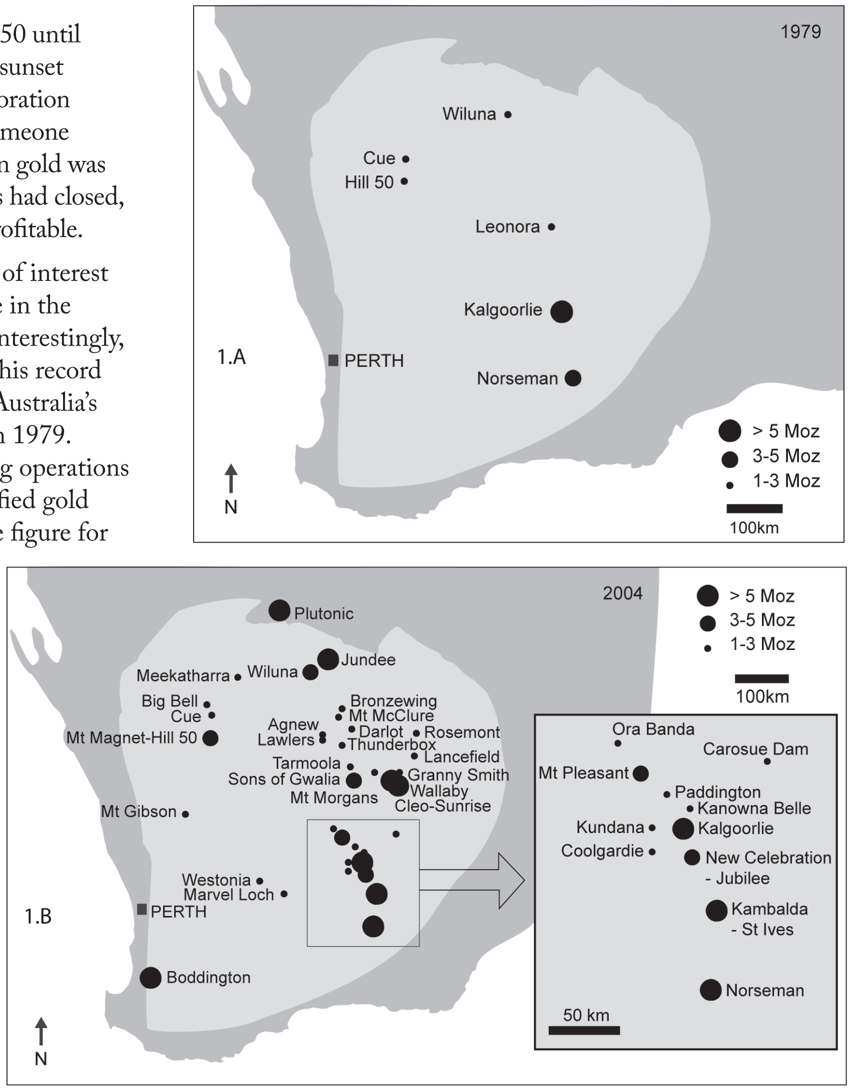

Fig 1. A) Significant gold producers known in the Yilgarn craton in 1979. All these goldfields were closed in 1979 except for Kalgoorlie and Norseman. B) Similar information to a) except updated to reflect 2004; and most of the shown goldfields were actively producing at this time.

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* *Note:* Mature *is not being used in a way that we would recommend, but in a way that reflects usage where a person wants to kill someone else's project: in such a context, it usually has negligible scientific basis.*

Interestingly, discovery measured as tonnes per year actually increased in the decade since these figures, and cost of discovery per ounce decreased. To put the Yilgarn success into context, this discovery performance has not been bettered in the history of gold, except by South Africa in 1886 and again in the 1930s.

The story of how the Yilgarn craton rose to become one of the World's premier gold producing areas by the end of the 20th century is not explained by gold price alone nor by machines and processing (shared by all nations). Critical to becoming a leading gold producer was some exceptional exploration from 1979 (nearly matched by USA and exceeding all other nations). The magnitude and the importance of this exploration success have both been under-estimated in summaries documenting this period in Australian gold: put simply, high price and great technologies count for naught if there is no resource base to mine.

This successful exploration drew significantly upon specific scientific breakthroughs applicable to Yilgarn gold, and these include the science of both primary gold and gold in the regolith (Hogan, 2004). These breakthroughs made a step change to exploration thinking (from which the industry never reverted), and the influence of the breakthroughs can be seen in most exploration by way of the geological parameters that became exploration foci. It is relatively easy to recognise three important scientific breakthroughs each for primary gold and regolith gold. All were virtually unknown in 1979, but by 1990 they were essential components of gold exploration programmes in the Yilgarn craton. Also, it needs to be appreciated that the uptake of ideas by industry was an important success factor. The story of the regolith breakthroughs is told elsewhere (Smith et al., this volume), and it was regolith science in the 1980s that identified several new districts of gold mineralisation (e.g. Plutonic). Many of these became open pits, and subsequently several became major underground gold mines. Here we focus on the *primary* deposits, their genesis, and their exploration.

Science of Gold Genesis, and Consequent Exploration Models

Emerging from World War II, global mineral exploration was focused on porphyry copper (1960s on, and led from the USA), and Archaean volcanogenic massive sulphide deposits (VMS deposits from 1970s, led by Canada). Very little gold research was generated prior to 1979, especially compared to a decade or two later. One immediate response to the rise of gold price was to apply the VMS genetic models to greenstone gold, and although initially this appeared attractive, the application was flawed and unsuccessful, and to some extent, those who stayed with VMS and syngenetic models longest did so to the detriment of their gold exploration and production.

A prescient regional metamorphic study in the Yilgarn craton was motivated primarily by interest in nickel (Binns et al., 1976; see also Binns, this volume). Such was its detail that this work made people think about gold and metamorphism. David Groves saw the importance here of the link to metamorphism, and sought support of the University of Western Australia to seed the Archaean Gold Project in 1979. The introduction of metamorphism into the thinking about Yilgarn gold was timely as research ideas were emerging from UK and eastern Australia on metamorphic fluids, fluid migration through deep crustal sequences, and the role of aqueous fluids during partial melting.

Table 1. Three scientific breakthroughs of lasting impact related to primary gold deposits of the Yilgarn craton (Hogan, 2004).

1	Epigenetic timing, structural control on deposits	Deposits formed after their host rocks, and were not formed on the seafloor
2	Direct link between carbonate alteration haloes and gold deposition	Carbonate part of gold event and not pre-conditioning, hence a direct guide
3	Nature and role of favourable host rocks, both chemically and mechanically	Within a district, some rocks are much more favourable hosts for gold deposits

The three parallel breakthroughs in regolith science related to gold dispersion in the regolith, preferred sampling media, and importance of considering landforms in planning exploration (Hogan, 2004).

All three ideas were in the public domain by 1981 and incorporated within most Yilgarn gold exploration (Phillips et al., 1983). Looking back from today, each breakthrough appears either obvious or even trivial; looking forward in 1981 each involved initial uncertainty and internal testing, followed by dissemination for public scrutiny which was accompanied by vigorous and animated challenge. Although beyond the scope of this abstract to mention all consequences of these three breakthroughs, one example can be mentioned and that is the repercussions of the epigenetic, rather than seafloor or syngenetic timing. Once Archaean greenstone gold ideas moved away from seafloor exhalations, the role of structural geology at these deposits was completely overhauled, fluid flow pathways during metamorphism became critical as did rock mechanical properties, and the concepts of stress mapping became an exploration tool. The science involved in these breakthroughs led directly to guides for regional and local exploration; one example is from the Eastern Goldfields region, a second example is from the Yandal gold province in the NE Yilgarn.

In the Eastern Goldfields, a simple prospectivity analysis in 1982 used a combination of host rock sequence, structural uplift and metamorphic grade, to highlight 20% of this area as being favourable for major gold deposits (Groves et al., 1987, figure 7). The analysis was, not surprisingly, successful when applied retrospectively to known deposits. Of greater interest though, exploration in the following 30 years has revealed many major finds in this part of the Eastern Goldfields belt and most in the highlighted 20%.

One regional application was to erect favourable criteria, and then, based upon their distribution, draw attention to the prospectivity of the whole Yandal greenstone belt several years before its major discoveries were made (Phillips and Vearncombe, 2011). In the up-until-then poorly auriferous Yandal greenstone belt of the NE Yilgarn craton, the three science breakthroughs of Table 1 led to practical exploration criteria, namely a focus on:

- **Gold:** meaning existing deposits and low-level but anomalous gold
- **Alteration:** meaning carbonate- and sulphide-bearing assemblages, and some gold-related elements
- **Lithology** which includes consideration of chemical and mechanical properties
- **Structure** with an emphasis on fluid channelways and focusing, including veining.

From the late 1980s, Yilgarn gold geology research took two main pathways. One involved the investigation of possible gold deposit formation from 180°C up to 740°C with variable involvement of lamprophyres and skarns (the continuum model led by University of Western Australia); and the other involved a metamorphic model of auriferous fluid generation near the greenschist to amphibolite facies transition of 400-500°C (the metamorphic model led by University of Melbourne). The two research pathways led to different exploration implications in high metamorphic grade terranes depending upon whether such deposits are considered metamorphic (continuum), or metamorphosed (i.e. Big Bell / Hemlo-type goldfields), and there are different implications for exploration especially in adjacent Proterozoic terranes.

Value and Application of Scientific Breakthroughs

The science breakthroughs, by themselves, did not make discoveries. Each underwent scrutiny by the geological community, but in each of the three examples, uptake by industry was fast. This effective uptake happened in an environment of rapid idea dissemination, and close and mostly informal industry-academia cooperation. Such dissemination commonly needed to be followed by specific training of geoscientists with respect to the new ideas, and brain-storming sessions on how the ideas could be applied, and where. A clear and consistent corporate management approach was useful, especially a continuous focus on discovery that pervaded geoscientists, engineers, metallurgists, accountants, administrators and CEOs. Unless this focus was pervasive and on-going, it was difficult for day-to-day exploration to remain concentrated on the tasks that led to discovery. A number of companies and individuals managed these facets well and made repeated discoveries.

One value of the science was to provide ideas and models that made sense (mostly) with the geology being mapped in the field: in time, minor refinements to the science were inevitable.

Another value of the science was to provide the rationale for ranking and selective data collection based on a viable genetic model. Hence, there was an important interplay between deposit descriptions and genetic models, and both were integral to success. This process and interplay would have been important even if all it did was to provide confidence and motivation, but it did more than this!

To gain full value from scientific breakthroughs, two commercial aspects need to be in place. The first is the assembly of a sizeable, and ideally contiguous, land package. This is especially important in the poorly outcropping Yilgarn craton in which determining the site of a discovery cannot be left to computers in Perth. In real life, Yilgarn exploration involves trial and error such that early results will be followed by either more closer-spaced exploration, or geographic shifts elsewhere towards more favourable areas. As a scientist with a bright new idea, it is discouraging having a single 100 hectare tenement on which to apply the idea: the idea might be excellent, but the tenement area barren.

The second commercial imperative is time. Relevant discoveries do not always follow within months of a scientific breakthrough. It takes time to work out what the breakthroughs mean, how they should be applied, and especially where they should be applied. As an example, regolith research was underway in the early 1970s (Smith et al., this volume), but the Plutonic gold deposit was not discovered until 1988 using regolith concepts. It would have been foolhardy to dismiss all regolith science because it did not find everything in the first year of its application. The three listed primary gold breakthroughs were publicly available in 1981 (Table 1), but their usage was still in its early days even into the late 1980s. The breakthroughs changed perceptions about certain regions; for example, Kambalda-St Ives was the site of gold discoveries in the 1980s adjacent to and south of nickel mines. Some deeper discoveries occurred in the Yilgarn in the early to mid-1990s (e.g. Bronzewing, Kanowna Belle, Jundee, Darlot): each directly or indirectly took advantage of the breakthroughs of Table 1 made available a decade previously.

At first glance, these factors of time and contiguous land packages appear to have no place in a discussion on science and discoveries. However, those who have been successful looking for gold in the Yilgarn craton have mostly appreciated this importance of time and of land, e.g. assembly of land parcels within the Yandal belt, Duketon belt, the districts surrounding Leonora, Mt Pleasant, Kalgoorlie, Kambalda-St Ives, Norseman, Southern Cross, Meekatharra, Big Bell-Cue, and more recently by Northern Star Resources Ltd, and companies in the Fraser Range. Without both time and land, the bright science ends up being a good idea that was never tested properly.

Acknowledgements

Many people, in universities and in industry, have contributed to the success of the Western Australian gold industry from the 1980s. David Groves saw the importance of the link to metamorphism, secured initial funding, brought the dimension of Archaean metallogeny to gold geology, and provided the experience to properly communicate the findings of the Archaean Gold Project. Later he established the prolific UWA Key Centre and produced many fine gold deposit studies. Julian Vearncombe played critical roles in the development and application of practical structural geology in gold exploration and mining, and this was especially so in the Yandal region in the 1980s and 1990s. Roger Powell and Janet Hergt provided high level petrology input into gold geology and led numerous student projects on specific mines; the lasting nature of their work is testimony to the quality of their science and the students. This publication is focused on the Archaean Gold Project and its findings, and then the application of these findings to exploration. Much research prior to 2000 has not been discussed here; more time will allow assessment of its usefulness in gold exploration and an opportunity to identify examples of success. The Archaean Gold Project was fortunate to involve students who made outstanding research contributions before going on to leadership roles such as Megan Clark, or on to exploration where they applied these ideas to make multiple gold discoveries such as Jeff Ion.

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Biographies

NEIL PHILLIPS is a geologist at the interface of exploration, mining geology, teaching and research—all with a focus on gold. He has played a major technical role in the Yilgarn goldfields and the opening of the Yandal gold province from 1980 onwards. He was Professor of Economic Geology at James Cook University, CSIRO Chief of Division of Exploration and Mining, and Exploration Manager for gold explorers. Throughout, he has maintained his passion for teaching and research on gold, integration with consulting, and developing research ideas that can generate different exploration opportunities. He has co-led the Melbourne Geology of Gold course since 1995, teaches thinking skills in his annual gold courses, and presents several industry gold short courses each year. He teaches at University of Melbourne, Stellenbosch University and Monash University in Melbourne, and collaborates with researchers in the study of granites, metamorphic petrology, fluids and field work. He is editor of Applied Earth Science (Transactions) journal, and editor of the AusIMM Australian Ore Deposits monograph.

EDUARD ESHUYS is the Chairman of Drummond Gold Limited, an Australian gold explorer. Mr Eshuys has been extensively involved in the discovery, development and operations of gold and nickel mines in Australia over the past 40 years. In 1996, he was awarded the Geological Society of Australia's Joe Harms medal for distinction in exploration success and project development. Eduard, a geologist, is a graduate of the University of Tasmania and a Fellow of both the Australian Institute of Company Directors and the Australasian Institute of Mining and Metallurgy.

Mining Booms in the History of Western Australia

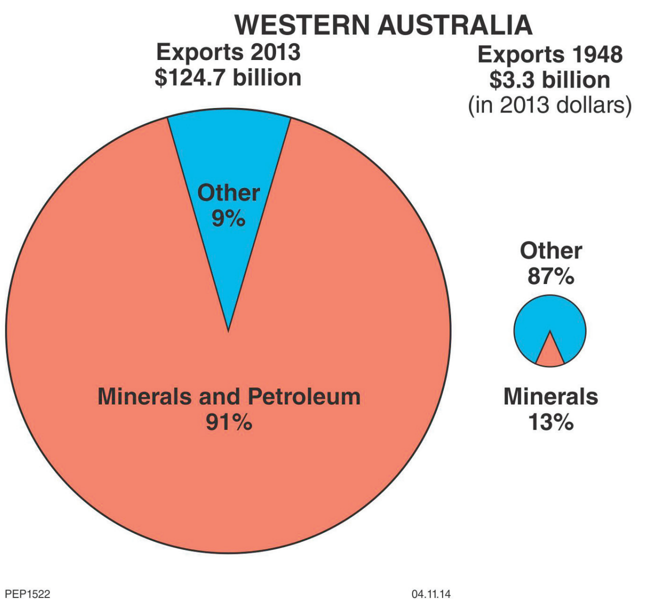
PHILLIP PLAYFORD[1]

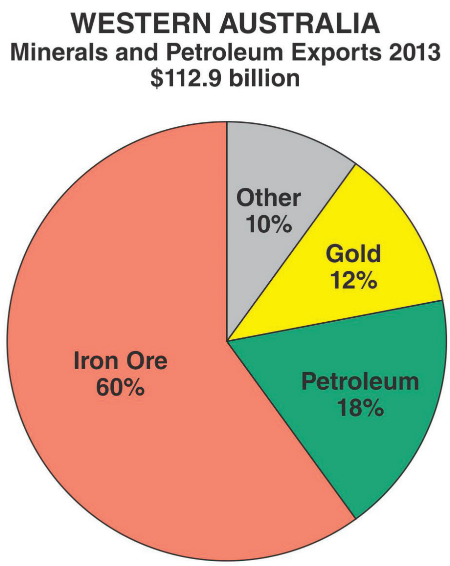
The economy of Western Australia has long been dependent on the mining industry as the mainstay of its economy. Lead mining began at Geraldine on the Murchison River in 1849, but the first mining boom resulted from the discovery of gold at Halls Creek in the Kimberley region in 1885. That find made headline news throughout the world, and although Halls Creek soon proved to be only a minor field, the resulting gold rush in 1885-86 attracted many experienced prospectors to the colony. After the disappointing outcome at Halls Creek they moved on to make economic gold discoveries during the following three years in the Pilbara, the Murchison, and Southern Cross. Those gold discoveries led on to the huge finds at Coolgardie in 1892 and Kalgoorlie in 1893. The population of the colony quadrupled in the decade of the 90s, turning Western Australia from being an impoverished colony into a wealthy state.

Gold production peaked in 1905 and slowly declined through to 1930. However it had a significant resurgence during the depression years of the 1930s, largely because of the entrepreneurial activities of Claude de Bernales, who promoted the WA gold-mining industry on the London stock exchange. Indeed, he was directly responsible for a minor 'boom' that kept Western Australia's economy going in those desperate years.

After World War 2 gold was still the mainstay of the State's mining industry, the only other mining activity being for coal at Collie and asbestos at Wittenoom, together with minor production of tin, lead and other minerals.

The announcement in 1953 of the discovery of oil at Rough Range, by West Australian Petroleum Pty Ltd, was arguably the most momentous event in Western Australia since gold was found some 50 years before at Kalgoorlie. Although the Rough Range field eventually proved to be uneconomic, its discovery reverberated around the world, and sparked a major boom on the stock market. As a result, oil and mining companies had little difficulty in raising capital, and in due course this led to successive discoveries during subsequent years, with a series of booms and mini-booms. The mining industry in this State, dominated by iron ore, is now one of the largest and most diversified in the world. It is not only Australia's biggest industry, it is also the backbone of our nation's economy. Without Western Australia's mining industry the country would be virtually bankrupt. Australia





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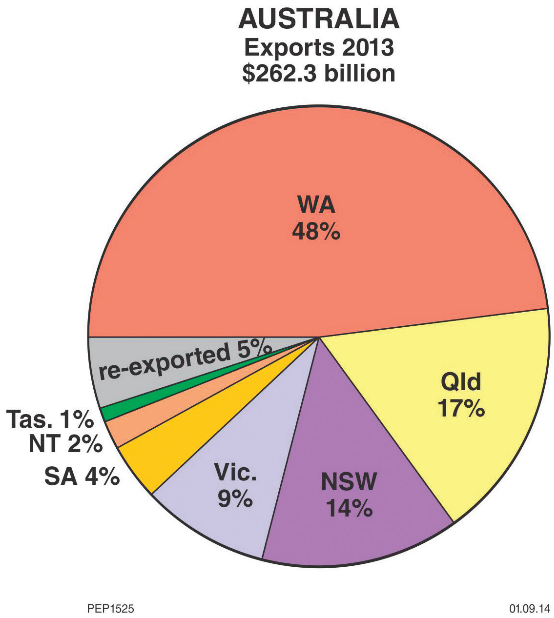
once rode on the backs of its sheep; it now rides on the dump-trucks of its mining industry.

On a personal note, I decided to become a geologist in 1948, while still at Perth Modern School. At that time very few people had more than a vague idea of what a geologist did for a living. My ambition was not made on the basis of potential income; it was because I wanted to lead an adventurous life, with a lot of time to spend in the Australian bush. In that ambition I have certainly not been disappointed.



Biography

PHIL PLAYFORD was born in Western Australia. He was awarded BSc (Hons) and honorary DSc degrees by The University of WA, and a PhD by Stanford University, which he attended with Fulbright and Hackett Scholarships. He has worked for both the WA and Federal Governments and the petroleum exploration industry, and is a former Director of the Geological Survey of WA and Assistant Director-General of Mines. His principal geological research has been in the Canning Basin (on Devonian reefs), Shark Bay, the Perth Basin, and Rottnest Island. Honours received include: Member of the Order of Australia (AM); Fellow of the Australian Academy of Technological Science and Engineering (FTSE); Lewis G Weeks Gold Medal of APPEA; Medal and Honorary Member of the Royal Society of WA; Gibb Maitland Medal and Fellow of the Geological Society of Australia; Special Commendation Award of the AAPG; Distinguished Honorary Member of PESA; and Honorary Member of the National Trust (WA). He is currently an Honorary Associate of GSWA and the WA Museum.

Mountains of Research and Innovation on the Yilgarn Plains

JIM ROSS[1]

Overview

This is the story of a 50 year march of geoscience research and innovation* (R&I) across the Yilgarn Plains. The rich endowment of this 680,000 km2 craton, and scale and pace of exploration and mineral development, spurred high levels of R&I, resulting in perhaps the most intensively studied, large scale, Archaean terrain on earth. R&I outcomes have in turn been looped back into the exploration, development and exploitation process, not only on the Yilgarn Block but nationally and internationally. These outcomes, and associated training, have led to the high international standing and effectiveness of Australian geologists and exploration technologies.

However, developments in R&I did not emerge of their own accord. They were underwritten by imagination, courage, commitment and risk investment from many individuals, organisations and companies that enabled geoscience R&I to prosper in WA. Key events and circumstances also contributed and these diverse factors catalysed a cascade of new developments in R&I that continue today.

Any attempt to track the history of geoscience R&I on the Yilgarn Block from 1950-2000 must first address the contexts within which it unfolded. For example, the scale and composition of changes to the State's economy and the links between key events, decisions and processes which catalysed these cascades of R&I.

This paper assesses economic contexts before addressing those key events, decisions and R&I developments which had such far reaching consequences. It then attempts to assess the value of the R&I effort from 1950-2000, in years of research effort and the funds committed, before analysing the source of those funds and their allocation to research organisations and other entities.

Economic Context

From 1950 to 2000 the character of the State's primary production fundamentally changed; from agriculture dominant in 1950, by a factor of 5:1, to minerals dominant in 2000, also by 5:1. Whilst the value of our world class agricultural sector almost trebled to about $7B, expressed in $2013/14**, the value of State's mineral production increased by a factor of about 60, from $574.5M in 1950 (WA Department of Mines, 1950) to $35B in 2000, a stunning increase that benefited geoscience R&I throughout the State.

Mineral production on the Yilgarn Block in 2000 is estimated at about $13.5B (largely gold, alumina and nickel), a twenty-four-fold increase over 1950 production of $558.4M. It equates to an average annual real growth rate of about 7%, over 50 years.

This growth in mineral production was not uniform and, after allowing for the small increase in value to 1960 (11%), the average annual real growth rate from 1960-2000 was 8-9%. Such a prolonged period of exceptional real growth explains the substantial R&I investment in WA which accompanied it. Uneven growth was exemplified by explosive growth of nickel from the late 1960s and of gold in the early to mid-1980s. The associated exploration booms and publicity only strengthened commitments to R&I by relevant stakeholders.

Early reports of the Department of Mines tell a story of increasing diversification of mineral production during the late 1950s and early 1960s, assisted by a lifting of the iron ore export embargo in 1960. For example, the 1960 Annual Report (WA Department of Mines, 1960) records that whilst gold and coal (Yilgarn Block) accounted for about 97% of total mineral production from 1900-1950, they averaged 80.4% from 1951-60 and contributed 72.4% in 1960, as iron ore and mineral sands production increased and iron ore exports commenced.

Increasing commodity diversification in the 1960s was underlined by opening of the Kwinana alumina refinery in 1963, the first shipment of iron ore exports to Japan in March 1966 (from Koolanooka), initial nickel production from Kambalda in 1967 and discovery of the Golden Grove VMS deposit and the Yeelirrie uranium deposit in 1971. This impressive rate of diversification could not be maintained and the remainder of the period to 2000 is dominated by the production of gold, nickel and alumina.

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* "Innovation" is used herein as a widely adopted positive change to prior practice, products, or operating models.

** All A$ monetary figures in this paper are expressed in A$2013/14, to provide a consistent basis for comparison, including with our current economy, costs and expenditure.

Gold, nickel, and to a lesser extent uranium, together with an enduring commitment to VMS deposits, have largely driven exploration on the Yilgarn Block and strongly influenced R&I. However, it is the extensive weathering and cover regimes that have demanded new R&I to unlock the latent potential. The response has been major, beneficial R&I programs in all the geoscience sub-disciplines, and also in drilling technologies.

Key Events and Developments

Pre 1950:

WMC Ltd was responsible for establishment of the alumina and nickel industries in WA and played a key role in survival of the gold industry through to the turn of the tide in the 1970s. The root causes of these remarkable achievements are found in its early history. WMC was formed in 1933 to explore and develop gold deposits in WA under the guiding principle that "success had to be achieved through exploration" (Clark, 1983). Unsurprisingly, it was an early adopter of new technologies and high level expertise introduced from overseas by the Company's London-based backers. These early commitments to exploration and R&I became embedded in the Company's DNA at all levels, where they successfully endured for more than 50 years and provided a successful model for the industry.

Four early examples suffice: reinterpretation of the Golden Mile by the McKinstry-led team of Gustafson and Miller in 1934 (Gustafson and Miller, 1937); flying detailed photography over more than 200,000 km2 of prospective greenstone terrain in the 1930s; flying an experimental aeromagnetic survey over an area north of Southern Cross in 1948; and applying ground magnetics and gravity to early stages of the search for a southern extension of the Golden Mile beneath cover.

1950-1965:

It was a challenging period for the gold industry with a fixed price and increasing costs; three developments assisted its survival. First was the successful introduction of tungsten carbide drill bits and light air leg rock drills in 1952 at the WMC-managed Central Norseman mines (Clark, 1983),following several years of internal development, innovations that increased productivity and were widely adopted. Second was introduction of a Commonwealth Government subsidy of up to thirty shillings per ounce for the gold industry in 1954. The third was increased productivity resulting from consolidation of mines in Kalgoorlie during 1950-55 by the WMC–managed Gold Mines of Kalgoorlie (GMK).

In 1960 WMC commenced a substantial research project, led by Guy Travis, based on detailed sectional documentation of the Golden Mile. Recognition of 10 zones within the Golden Mile Dolerite led to reinterpretation of the stratigraphy and structure (Travis et al, 1971; Bartram et al, 1971) to guide mine exploration. It also enabled accurate interpretation of controls on mineralisation at GMK's large, low -grade Mt Charlotte deposit which was followed by a successful deep drilling program. The subsequent underground bulk mining operations were an important factor in the survival of gold mining in Kalgoorlie. In the early 1960s WMC also used its air photography from the 1930s to assist detailed mapping from Kalgoorlie to the old Red Hill Gold mine at Kambalda, applied research that aided early assessment of the Kambalda nickel prospect.

The gold struggle led to the 1953 decision by WMC to explore for other metals and the gold mines it managed in Kalgoorlie, Norseman and Southern Cross-Bullfinch became a critical source of skills and experience to assist new mineral developments. Notably the iron ore development at Koolanooka, early stages of the Darling Range bauxite venture, and rapid development of the Kambalda nickel discovery.

This period also included two historic events in WA's mineral history. First was the bold and courageous decision by WMC to acquire a 16,000 km2 Temporary Reserve over the Darling Range bauxite deposits in the mid-1950s, following reconnaissance exploration. These supposedly low-grade extensive deposits were rich in silica which proved to be free quartz. Furthermore, the aluminium was essentially in gibbsite, which dissolves in caustic soda at much lower temperatures than boehmite and diaspore, without dissolving free quartz. It became evident that caustic soda consumption would be much lower, and the economics more favourable, than previously assumed; an observation attributed to Roy Woodall.

Successful delineation and development of these deposits, led by a relatively small company, laid the foundation for a major new export industry for the State. It also led to development of the vacuum drill which enabled high integrity sampling of the weathered zone inside the drill stem, a principle subsequently adopted into air core drilling and also applied to percussion drilling by WMC in the early 1960s.

The second historic event was lifting of the iron ore export embargo in 1960, with its enormous economic consequences for the State. On the Yilgarn Block it led to WMC's successful and profitable development of the Koolanooka iron ore deposits (source of WA's first iron ore exports to Japan in 1966) and a cash flow that helped to maintain its 20% equity and leadership role in ALCOA, and fund early stages of Kambalda exploration.

These historic events and associated activity, together with increasing interest in the latent potential of WA's extensive Archaean cratons, most likely led to the far reaching decisions in 1960 to immediately double the size of the Geological Survey (from 11 geologists in 1961 to 25 in 1962) and accelerate the limited four mile mapping (1:250,000) of the State. They probably also influenced the CSIRO decision to establish a Perth branch of the Division of Applied Mineralogy in 1963. This branch did not impact on exploration until 1968, but provided a foundation for much of CSIRO's subsequent diverse and important contributions to exploration geoscience R&I over more than 40 years.

1966-1976:

This decade is like no other in the history of Yilgarn Block exploration, sparked by WMC's discovery of the high-grade Kambalda nickel sulphide deposits in January, 1966. The frenzy of subsequent exploration activity, discovery and stock market speculation was amplified by the unforgettable boom in Poseidon shares in 1970. The resulting discoveries, and investment in nickel, laid the foundations of a substantial new industry.

Modern base metal exploration arrived in force from all directions, onto the relatively blank page of the Yilgarn Block; almost anything seemed possible. This belief was reinforced by the continuing discovery of nickel sulphide deposits until 1974, the discovery of Golden Grove in 1971, which kept the VMS dream alive, and of the substantial Yeelirrie calcrete uranium deposit, also in 1971. The high levels of activity, anticipation and publicity had widespread impacts, including continuing growth of GSWA to 50 geologists in 1972.

The substantial Kambalda deposits represented a new class, in terms of both their komatiitic host rocks and mineralisation. They were fertile ground for applied and fundamental research, and required that conventional wisdoms about the origin of the greenstone belts of the Yilgarn Block be reconsidered. These factors are likely to have contributed to the key 1968 decision by GSWA and Curtin (then WAIT) to establish a geochronological capability at Curtin under the leadership of John de Laeter (de Laeter, 2008).

Naturally WMC pursued a vigorous applied research program, including establishment of the Kambalda research laboratory, by the author, in 1970. This laboratory was continuously active until 1994. In 1968 the CSIRO Division of Applied Mineralogy amended its research mission to support the Australian minerals exploration industry and immediately invested in strengthening its WA Branch, focussing on processes of ore formation, including nickel, and the geochemical and mineralogical processes of weathering. Finally, in 1972, UWA responded with the key appointments of David Groves and Ray Binns to provide it, for the first time, with significant capability in economic geology-oriented research. This firepower was soon aimed at the Eastern Goldfields and nickel sulphides through personal and post graduate research.

As outlined elsewhere (Gresham, 2015), the discovery of Kambalda was built on mapping, gossan geochemistry, electrical geophysics (IP), and reinforced by Richard Mazzucchelli's soil geochemistry. Each of these technologies, together with BMR one mile aeromagnetics and basic geology, were harnessed to exploration targeting. They also spurred applied R&I, particularly within WMC and CSIRO. R&I also spread to remote sensing, tectonics (Tim O'Driscoll) and geobotany in the search for a competitive advantage.

Rotary air blast (RAB) drilling played a key role in combating cover and deep weathering, and intensive geochemistry benefited from the prior commercialisation of AAS. The presence of massive sulphides favoured electromagnetic geophysical techniques over IP, and CSIRO's SIROTEM and subsequent EM research programs, flowed from its early interest in improving the Russian-built TEM system acquired by WMC.

This remarkable decade began with a bang, but ended in a whimper. By 1976 many overseas exploration groups had withdrawn as a result of Whitlam Government policies. Nickel prices were low and only two gold mines were operating, Central Norseman and Mt Charlotte (Hopkins, 1993), both managed by WMC. Not even the faint flicker of hope in a slowly improving gold price, nor some nuclear-fuelled uranium exploration, could reverse the fast fading light of an unforgettable boom.

1977-2000:

Expansion of the alumina and nickel industries continued, but the big story was increasing gold prices and the revival and unparalleled expansion of the gold industry, particularly on the Yilgarn Block. Suspension of US$ backing for the gold price in 1971 led to gradual price increases which accelerated in the late 1970s and surged to US$800/oz in 1980, after OPEC trebled oil prices. The ensuing gold exploration and development boom led to rapid expansion of the number of gold-producing companies on the Yilgarn Block. Shallow, low-grade oxide ores were exploited around known deposits, tailings were retreated and hard rock mines redeveloped, most notably the superpit in Kalgoorlie; all indebted to carbon-in-pulp (CIP) extraction technology.

The 1980s resulted in significant and wide-ranging R&I developments, mostly driven by successful gold exploration. Examples include: important advances by CSIRO in understanding the weathering and cover profiles exposed in the oxide gold open cuts (led by Charles Butt); advances in laterite geochemistry (led by Ray Smith); increasing expertise in orogenic gold deposits under the leadership of David Groves at UWA, reinforced by establishment of the Key Centre in 1987; initiation of 1:100,000 scale mapping by GSWA (Tim Griffin) in the Eastern Goldfields in 1980, following completion of the four mile mapping coverage; and application of single crystal zircon dating technology by Bob Pidgeon which stimulated purchase of the first SHRIMP in 1993. This instrument and its successors have revolutionised geochronology in the State;

Other examples include multi-client, high resolution aeromagnetic surveys over the greenstone belts by Aerodata (led by Pat Cunneen) and associated interpretation of solid geology (David Isles); increasing resolution in airborne and ground magnetic surveys, in recognition of the importance of structural controls on most gold deposits; development of BLEG sampling, thanks to the metallurgist, Bill Griffin; successful development of low level gold geochemistry by WMC as an alternative to BLEG; adoption of ICP and XRF analytical techniques; development of MMI geochemistry by Alan Mann; development of a software industry in Perth for 3D visualisation of exploration data; and adoption of air core drilling (first patented in WA in the early 1970s) to improve sample integrity in the weathered regime and beneath cover, as the significance of very low level gold anomalies was increasingly acknowledged.

The 1990s saw continuing progress in basic and applied R&I. Notable developments included: increased emphasis on geochronology, following commissioning of SHRIMP A; increasing numbers of PhD graduates from the Key Centre, which developed an international reputation, especially in the study of orogenic gold deposits, based on Yilgarn research; significant advances in the manipulation and integration of exploration data; and successful establishment of CRC LEME, which brought much of CSIRO's exceptional work in weathering and landscape evolution on the Yilgarn Block to an integrated conclusion; Importantly, much R&I was supported by industry, via AMIRA, MERIWA, and direct grants. By 2000, GSWA employed 63 geoscientists; the John de Laeter Centre had been established; automated logging was in its infancy; hard rock seismic was emerging, and the concept of 4D predictive modelling of mineral systems to increase exploration effectiveness had been conceived.

The Mountains of Research and Innovation

Following extensive consultation it is conservatively estimated that the contributions to R&I directly related to the Yilgarn Block from public institutions, including GSWA, and some companies, total almost 2000 years of professional geoscientist time, an average of about 40 full time geoscientists each year of this 50 year period. Unsurprisingly, GSWA accounts for slightly more than 50%, followed by CSIRO and UWA, then WMC.

Total expenditure from all sources, including capital, non-professional staff, and industry contributions (direct and via AMIRA and MERIWA), is conservatively estimated at more than $480M, with the State Government (principally GSWA) contributing 58%, industry 22% and the Commonwealth about 16% (predominantly CSIRO). The industry contribution is dominated by WMC and Aerodata internal R&I, followed by AMIRA funding in excess of $20M. A detailed breakdown of R&I time, expenditure, key sources of funds invested, and the entities responsible for expenditure is included in the presentation.

The events of this 50 year period have transformed the State's economy; they have also transformed geoscience in WA, and led to high levels of institutional and industry cooperation. As a consequence, we can be proud of WA's leading role in understanding Archaean tectonics and its mineral systems, the international standing of Australian geologists and the technologies they apply, and the exceptional infrastructure that underpins basic and applied geoscience research in WA.

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Biography

JIM ROSS is a graduate of UWA and the University of California, Berkeley, with over fifty years' experience in exploration, development and mining, including 25 years with WMC and > 25 years corporate experience. He is currently Deputy Chairman of Berkeley Resources Limited.

Jim's experience includes >30 years at the interface between industry, education and research, where he has led several key geoscience initiatives. He chairs the John de Laeter Centre and is a member of the Technology Industry Advisory Council. He holds an Honorary DSc from both UWA and Curtin and was made a Member of the Order of Australia for services to geoscience.

Regolith Research for Mineral Exploration

RAY SMITH, CHARLES BUTT and RAVI ANAND[1]

This paper focusses on research into regolith geology and exploration geochemistry on the Yilgarn Craton over the three decades to the year 2000.

The use of geochemistry for mineral exploration in Australia was tested sporadically by industry and the Bureau of Mineral Resources (now Geoscience Australia) from about 1947. However, apart from studies near Tennant Creek, NT and Cobar, NSW, most tests were in areas of high relief rather than deeply weathered regions such as the Yilgarn, and usage lagged in comparison with East Africa.

Publication of the classic volume by Hawkes and Webb in 1962, coupled with the development of the atomic absorption spectrophotometer for chemical analyses, stimulated widespread application of geochemistry across Australia through the 1960s. Richard Mazzuccchelli's PhD research into Au-As geochemistry was a pioneering regolith study in the Eastern Goldfields of the Yilgarn. With the discovery of nickel sulphides at Kambalda in 1966, geochemistry became one of the dominant exploration tools. However, it soon became apparent that its use was not straightforward. The abundance, age, and complex history of the regolith, the profound chemical, mineralogical and physical changes that had occurred during its formation, and its very thickness, together with the presence of extensive areas of transported cover, were significant hindrances. This prompted long-term research activities in step with industry needs, commencing with nickel, base metals Cu-Zn, then Au, from the early 1980s. Collaboration involved government research and survey agencies, universities and industry and, despite various vicissitudes, is still ongoing.

The research had three overlapping themes: *determining the nature, distribution and genesis of regolith materials; establishing processes of weathering and geochemical dispersion during regolith formation over time; and developing appropriate geochemical exploration procedures.* The research led to regolith geology and geochemistry becoming fundamental and indispensible components of exploration programs and has resulted directly or indirectly in numerous ore deposit discoveries in the Yilgarn, elsewhere in Australia and overseas.

Major Exploration Issues in the Late 1960s

Exploration almost always started in areas of outcrop or subcrop. In the Yilgarn, rocks are so deeply weathered that identifying original bedrock was commonly difficult and confusing. Classical geological training in igneous, metamorphic and sedimentary petrology did not prepare graduates for working with such weathered rocks. Problems were exacerbated in logging cuttings from rotary and percussion drilling. Regolith courses addressing these issues were nonexistent.

A long-standing approach for base metal exploration in Australia is to seek and sample gossans and this was the initial approach for Ni sulphide exploration in the Yilgarn. However, long periods of lateritic weathering produced an abundance of 'ironstones', many of which may be confused with gossans or were gossans derived from barren sulphides. It became apparent that not all Ni-rich ironstones and soils were derived from Ni sulphides – and, conversely, that not all gossans and associated soils derived from Ni sulphides were Ni-rich. Secondary enrichment of Ni (±Co, Mn) to form low-grade Ni laterites over ultramafic rocks resulted in widespread 'anomalies' in saprolite, soils and ferruginous ironstones, whereas some gossans derived from Ni sulphides could be highly leached of Ni, Cu or Co. Statistical procedures, based on multi-element analyses, were developed for discriminating Ni gossans. Discrimination was imperfect but nonetheless most of the principal Ni deposits in areas of outcrop and residual soil were discovered at this time. Thereafter, the importance of gossan and soil geochemistry for Ni exploration declined. The complexity of the regolith over much of the Yilgarn Craton prompted the use of drilling to sample bedrock in preference to surface media. The principal difficulties were a poor understanding of the landscape, the nature and evolution of regolith and their combined influence on the surface expression of mineralization.

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A New Strategic Research Program

In 1950, CSIRO mineralogist Arthur Gaskin suggested that Australia should develop geochemistry in a rigorous, scientific manner as a long-term commitment. In the late 1960s, he developed a strategic research plan to tackle Australia's deeply weathered terrains, focussed initially on the Yilgarn. A new CSIRO group would be formed at Floreat, WA, complementing strengths at CSIRO North Ryde in Sydney. This initiative received logistical support from Western Mining Corporation and endorsement from CSIRO's Western Australian Advisory Committee, chaired by Sir Laurence Brodie-Hall. First appointments were made in 1971. For the first 15 or so years, a wide diversity of projects tackled some fundamental geochemical and mineralogical aspects of weathering of Ni and base metal sulphides, regolith mapping and characterization, developed the use of lateritic pisolith, nodule and duricrust sampling, building on the study by Mazzucchelli, and studied the geology and hydrogeochemistry of calcrete uranium mineralization and the chemistry of gold in the surficial environment. Research by the GSWA and industry tackled gossan discrimination, and collaboration by geochemists across the country led to the compilation of exploration case histories and their summary of dispersion characteristics as models based on landscape geochemistry. This early work was the basis for a series of industry-sponsored projects in regolith geology and geochemistry through AMIRA, from 1987 to 2013. The research was broadened further by the establishment of the Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME, 1995-2001) and its successor (2001-2008), which operated Australia-wide. Courses, which had already been under way at universities in Perth (1970s) and Hobart (early 1990s), were expanded to Canberra and Adelaide through CRC LEME, with professional development courses delivered to industry publically or on-site. Results were published as reports, atlases and maps, and in national and international journals.

Nature, Distribution and Genesis of the Regolith

Regolith-landform mapping was commenced by CSIRO in the 1950s and 1960s (as 'Land System' mapping), initially for defence, agricultural and rangeland purposes. It is based on the premise that there is commonly a correlation between landform, vegetation and underlying regolith, so that mapped units can have specific associations of landform, regolith materials, and, possibly, bedrock geology. The implications for mineral exploration were first applied as part of a geochemical dispersion study of the Mt Keith nickel sulphide deposit (from 1972), culminating in a 1: 250 000 regolith landform map and report for the Sandstone-Mt Keith region.

Later studies focussed on selected orientation districts and studies (e.g. Lawlers in 1987) distributed across the present-day rainfall gradient. Each incorporated a three-dimensional synthesis of regolith-landform mapping, regolith stratigraphy from drilling for that purpose, characterization of materials using standardized terminology, classification and coding, and the dynamics of regolith facies relationships. A long-term activity of regolith dating was initiated within CRC LEME. Mapping was based on field traverses and interpretation of aerial photographs, utilising satellite, radiometric and airborne spectral imagery as these technologies developed, with additional third dimensional information supplied by airborne and ground electromagnetic and magnetic surveys. Regional regolith landform maps were also prepared by the GSWA for their regional regolith geochemical maps series (1994-2002). Research also focussed on an understanding of processes of weathering and geochemical dispersion, and the mineralogy and petrography of weathering profiles over different bedrocks. The broad framework arising within the CSIRO-AMIRA projects and within CRC LEME provided the necessary control for planning mineral exploration and interpreting geochemical dispersion patterns. Regolith-landform maps and syntheses became essential components of regional, district and near-mine exploration programs - a substantial step change in mineral exploration.

Processes of Weathering and Geochemical Dispersion

Knowledge of chemical, mineralogical and physical processes is essential to understanding geochemical dispersion. Initial work concentrated on details of the oxidation of Ni sulphides and the formation of gossans, and subsequently extended to a landscape scale. One such study was of the genesis of calcrete uranium deposits, essentially a contemporary, active process. In comparison, the formation of supergene gold deposits was shown to be the product of several phases of weathering: an early phase that concentrated gold in lateritic residuum (e.g. Boddington, Mt Gibson), later reworking under acid saline conditions in the southern Yilgarn and Gawler Cratons, and currently active biogenic dispersion into vegetation (a theme expanded from 2004 onwards) and pedogenic carbonates.

Landscape geochemical models were also the product of collaborative projects based on assembling geochemical case histories illustrating dispersion in different climatic, landscape and regolith environments across Australia, with the Yilgarn forming an important component. These compilations were published in 1980 and 2005, with the results summarized in conceptual models that describe geochemical dispersion and exploration techniques. Yilgarn-specific, comprehensive three-dimensional models were developed and tested successfully within the CSIRO-AMIRA projects, and similar models are also the focus of an exploration guide for the Yilgarn published in 2010.

Geochemical Exploration Procedures

Development and assessment of exploration techniques have been important research goals. Research emphasised the use of specific regolith sample media and sampling procedures as guides to ore deposits – as well as showing which procedures were not effective. Use of multi-element geochemistry was facilitated by further advances in chemical analytical methods from the 1980s onwards, by broadening element suites, lowering detection limits and reducing costs. Research also included statistical data analysis, evaluation of partial chemical analytical techniques and applications of hydrogeochemistry, biogeochemistry, and gas-vapour geochemistry.

Laterite, lag and calcrete geochemistry are important examples of techniques exploiting geochemical dispersion under different weathering episodes. Widespread cover of lateritic duricrusts and gravel was once considered a substantial impediment to mineral exploration. However, research from the late 1970s onwards revealed multi-element geochemical haloes in both exposed and buried lateritic residuum, ranging from $1 km^2$ in area (Golden Grove Cu-Zn-Au deposit) to $>100 km^2$, (Greenbushes rare metal pegmatite deposit), each halo presenting a multi-element target. Subsequent applications using regional (3 km sampling) to district and local (1 km and closer) sampling of lateritic residuum and lateritic colluvium contributed to many Au deposit discoveries, including the Johnston Range Au deposits (1986, Australian Business), Bronzewing (1992, beneath 20 m of cover), Jundee (1992) and Nimary (1993).

The regional surveys also demonstrated the existence and exploration significance of chalcophile element corridors (appearing to be tectono-stratigraphic features of basement) that cross parts of the Yilgarn. Sampling lateritic residuum has also been used to prepare a multi-element geochemical map of the western Yilgarn based on sampling at 9 km intervals. The anomalous geochemical response is largely due to residual accumulation of indicator elements in iron oxides, and accumulation and mechanical dispersion of resistant minerals and clasts during lateritic weathering. In comparison, active, probably biogenic mobilization results in preferential concentration of gold in pedogenic carbonates. This phenomenon was first noted in the late 1980s and was quickly established as the basis for a successful sampling procedure in areas of residual soil and shallow transported cover in the southern Yilgarn, contributing to the discovery of many gold deposits (e.g., East Kundana, Base Line, Golden Cities, Ghost Crab, Twin Peaks-Karari). Calcrete sampling was also instrumental in revitalizing exploration in the Gawler Craton, SA, including discovery of the Challenger Au deposit.

Key Ingredients for Success

- The whole cycle of research, exploration trials, technology transfer and successful application takes substantial time. Pay-offs occur progressively, over 30 years or more.
- Strategic research programs can initially have modest staffing and budgets, growing when successful.
- Success requires a broad vision and strategic plan. The plan will likely evolve – but should be adhered to.
- Strategic research requires long-term commitments - from industry, State and Federal institutions, universities and funding bodies.
- Commitments, once made, must not be taken for granted. Researchers need to be powerful champions of their causes within their organisations.
- Researchers need plenty of scope to take initiatives, show innovation, and grasp opportunities within the strategic direction.
- All the key studies were multidisciplinary.
- Key researchers need to understand the mineral industry, and to maintain dialogue with business media.
- Experience transfer between researchers and company users needs to be two-way, continual, and involve workshops in the laboratory and in the field.
- Where research contributes to or leads to new approaches, better practice or discovery of new resources, high-level industry feedback to the upper levels of research organisations and to politicians is more than a nice thing to do. This could make the difference between a research group flourishing or being axed.

Acknowledgements

Although CSIRO had the largest presence in regolith research in the Yilgarn during this period, both independent and collaborative research was also undertaken by GSWA, BMR-AGSO-GA, WAIT-Curtin University, the University of WA, and numerous mining and exploration companies and consultancies, all of whom we acknowledge. Input to this paper by Neil Phillips and David Groves is appreciated.

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Biographies

RAY SMITH has Bachelor Honours (1963) and PhD (1967) degrees in geology from the University of Sydney. He was a Postdoctoral Fellow at the University of Manitoba, and a Faculty member as Research Associate at the State University of New York, Binghamton. On returning to Australia, he was appointed Research Manager then Exploration Manager, WA, for Union Miniére Development & Mining Corp. Ltd. He joined CSIRO in Perth in 1973 as a Senior Research Scientist working on research for mineral exploration with emphasis on regolith environments. Ray was promoted to Chief Research Scientist and thereafter CSIRO Fellow. From 1995 to 2002, he was CEO of the Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) and its successor, the CRC for Landscape Environments and Mineral Exploration. For 20 years he was also an Adjunct Professor at Curtin University's Applied Geology School/Department. Ray has received national and international awards for research in collaboration with the mineral industry including a Gold Medal from the international Association of Exploration Geochemists/Applied Geochemists. In 1997, he was elected a Fellow of the Australian Academy of Technological Sciences and Engineering. For the last 12 years in "retirement", Ray has been continuing his research as an Emeritus Fellow with CSIRO.

CHARLES BUTT is an Honorary Research Fellow with the CSIRO Minerals Resources Flagship. He was previously Chief Scientist for the CSIRO Division of Exploration & Mining, and Deputy Director and Program Leader of CRC LEME. He was appointed Fellow of the Australian Academy of Technological Sciences and Engineering in 2004 and CSIRO Fellow in 2007. Charles has over 40 years research experience in exploration geochemistry and regolith geology, mainly in developing procedures for gold, nickel, PGE, uranium and base metal exploration in deeply weathered terrains, and in the geology of secondary mineral deposits, particularly nickel laterites, supergene gold and calcrete uranium. He has led many industry funded research projects in Australia, and undertaken consultancies and delivered courses and field workshops to industry, universities and government in Australia, N & S America and Africa. Charles has authored over 250 papers, edited monographs and reports, and was Associate Editor for Journal of Geochemical Exploration, and Geochemistry, Exploration, Environment, Analysis (1976-2010). He is recipient of the Gold Medal of the Association of Applied Geochemists, the Science and Technology Award of the Association of Mining and Exploration Companies, and the Gibb Maitland and A.B. Edwards Medals of the Geological Society of Australia.

RAVI ANAND is a Chief Research Scientist at CSIRO and an Adjunct Professor in regolith geology and geochemistry at Curtin University, Perth, Western Australia. He joined CSIRO in 1987 as a Research Scientist in the Division of Mineralogy, carrying out research into methods of exploring for concealed mineral deposits in Australia's deeply weathered terrains. Ravi was Applications Coordinator of the CRC for Landscape Evolution and Mineral exploration (1995-2001) and Program leader of Program 2 for Landscape Environments and Mineral Exploration (2001-2008). He has over 30 years research experience in regolith geoscience and exploration geochemistry, mainly in developing procedures for gold, base metals and bauxite exploration in deeply weathered terrains. His current research in collaboration with the minerals industry is focussed on understanding metal dispersion processes through transported cover. He has received national and international awards for regolith research in collaboration with the mining industry.

Western Yilgarn: the Quiet Achiever

SIMON A. WILDE[1]

The Western Yilgarn was my first 'stomping ground' as a graduate geologist. On arriving at the Geological Survey of Western Australia (GSWA) in early January 1972, a number of things surprised me: (i) that the 1:250,000 sheet in which the State Capital is located had never been mapped (at least, the 'hard rock' part), (ii) that there were huge forested areas in the SW of the State (somehow this information had never permeated overseas), and (iii) that there were massive bauxite reserves in the Darling Range (another well-kept secret) – and that I was supposed to work on them!! However, as a prelude (and, I suspect, a sweetener), I was to map the Yilgarn Craton components of the Perth and Pinjarra 1:250,000 sheets; later extended to the two sheets to the south (Collie and Pemberton-Irwin Inlet). As someone keen on Archean geology and high-grade metamorphic rocks, I felt at the time that there could be no better job in the world.

The Perth Sheet posed some interesting and rather unique challenges. It was explained to me how many days I should spend on each 1:40,000 compilation sheet in order to complete the 'standard' regional 1:250,000 map - GSWA-style. However, even before going into the field, Professor Rex Prider had introduced me to a treasure-trove of information in the form of all those UWA Honours theses he had supervised on various aspects of the Chittering and Jimperding 'series'. There was a mass of information here and I had this uneasy feeling that there was going to be a problem with me racing around in a 4WD and stopping every five-or-so kilometres and the amount of information that lay beneath the covers of each and every one of those theses.

So, after checking it really was 'granite' on the Darling Scarp near Kalamunda, as the Perth Basin mappers had shown, I was let loose on the northern part of the sheet with a trusty old caravan and my own brand-new Landrover. It had been mentioned that the Director was unlikely to approve staying in caravan parks, so I parked the caravan on what appeared to be vacant land not far from the Mogumber Station - but in sight of the pub. The caravan had a kerosene fridge – something I perceived was unique to the antipodes – and, after stomping-out the mini bushfire I had caused when I whizzed the kerosene 'starter' out of the caravan door after my first failed attempt to light it, I was ready to start. Interestingly, the outcrop was not great and I think for the first two weeks I was on schedule to complete the field mapping in the requisite time. However, it was not to last. As I headed south toward Bindoon, the Chittering belt widened and I made my first executive decision: in the areas previously mapped by university students and/or their professor, I would ensure that I potentially knew as much as they did! So the pin pricks in my aerial photos – as Dennis Gee has outlined – increased in density, forcing me to make another decision at odds with GSWA policy: I would simply indent the photos with my pen, thereby preserving the surface and hopefully ensuring that I could still observe all the features in stereo.

Geologically, tracing out the Chittering Metamorphic Belt, and later the Jimperding Metamorphic Belt around Toodyay and environs, were the highlights of mapping the Perth Sheet. Variations in lithology and metamorphic grade were obvious in the field – and greatly enhanced when I began to get thin sections of the key rock-units. Indeed, attempting to map out the isograds in the Jimperding belt was rewarding, with a general eastward increase in grade, unrelated to and thus pre-dating, the granites of the Darling Range Batholith. The low-pressure/high temperature nature of the Jimperding belt was in marked contrast to the Chittering Metamorphic Belt, which had medium pressure/medium-high temperature assemblages, perhaps related to the fact it tracked the line of the Darling Fault with the strong but patchy development of mylonites close to the Darling Scarp.

The Pinjarra Sheet contained only a thin sliver of the Jimperding belt near Beverley, whereas the Chittering belt had not continued beyond South Chittering, immediately north of where the Avon/Swan River emerged onto the coastal plain. However, deformation of the granites increased in intensity near Pinjarra and supracrustal remnants are present near Waroona.

Importantly, the Pinjarra Sheet had a secret to reveal. In the forested area that extended from just east of the Darling Scarp all the way to the Albany Highway lay an unknown greenstone belt almost entirely hidden beneath a carapace of laterite. I remember calling on Tony Smurthwaite (then with Alcoa, but later with the GSWA) before entering this area and he told me – almost in the manner of a horror movie

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– that 'strange rocks' may be present in there. He did not elaborate, but it did heighten my anticipation that perhaps I would be fortunate and at least find a few rocks, since nothing definite appeared on many of the aerial photographs. From experience in the forest north of Bindoon, I had noted on aerial photographs similar incisions into the laterite surface on the flanks of Mount Saddleback and Mount Wells. These provided the only sites where bedrock may potentially be exposed and so were marked for investigation.

Klaus Hirschberg had joined the GSWA as a hydrogeologist – but was immediately assigned to assist me with mapping the remainder of the Pinjarra Sheet. On the same day, we both had a Eureka moment. I was mapping in the edge of the forest just north of the Hotham River when I came across what at first I thought was a continuation of the Cardup Group, a sequence of turbiditic sediments exposed along the Darling Scarp from Maddington to Serpentine – but what were they doing so far south and so far inland? On further investigation, it appeared that there were pyroclastic rocks in amongst the sediments!! When I got back to the caravan that evening and told Klaus what I had found, he explained to me he had found some fine-grained mafic rocks with a strong foliation near Mount Saddleback. We went out together the next day to investigate these and it was clear that they were not deformed dolerite (as geologists at Alwest and Reynolds had believed), but metabasalt. Although at that stage in my career I had never seen a greenstone belt, it became immediately obvious that, indeed, this is what we had found. Subsequent mapping revealed those incisions of the laterite on Mount Wells exposed felsic volcanic rocks whereas those on Mount Saddleback exposed metabasalt. When reporting this find on my return to the office, it caused a bit of a stir, and I was given the go-ahead to map the area in detail (Wilde, 1976). Later, Richard Davy, the GSWA geochemist, organised geochemical analyses of my field samples and one andesite revealed elevated values of copper. This was followed up by Richard undertaking a soil and stream sediment survey in which further anomalies were identified. Armed with this information, Richard and I called in representatives of both Alcoa and Reynolds – who held the bauxite leases in the area – where we divulged our findings. Alcoa were interested, but not overly excited, whereas Reynolds were far more excited and followed this up with a re-investigation of the bottom-hole samples in the numerous vacuum drill holes they had put down for bauxite delineation. They came up trumps – identifying what was to become the main Boddington gold deposit on the flanks of Mount Wells. Interestingly, the boundary between the Alcoa and Reynolds leases split the mineralised area, and Alcoa would eventually open up the Hedges deposit right next to the Reynolds mine.

The Collie Sheet to the south is largely covered by granites. However, supracrustal rocks along the Darling Scarp appear again near Brunswick Junction and then widen southward toward Balingup and Bridgetown (defining the Balingup Metamorphic Belt). The latter shares a mixture of features in common with both the Chittering and Jimperding belts, with mafic rocks recording the same medium pressure/ medium-high temperature assemblages as the Chittering belt, but with prominent fuchsitic quartzite units, as in the Jimperding belt, also being present at Bridgetown. In addition, this belt hosts the Greenbushes Pegmatite, which has been a major producer of tin, tantalum and lithium during the period under discussion. There are also some interesting sedimentary rocks, with the Donnybrook Sandstone and Maxicar Beds developed along the Darling Fault and the Collie Basin containing the only operating coal mines in Western Australia. Both the Collie and Pemberton-Irwin River 1:250,000 sheets were mapped jointly with Ian Walker.

The Pemberton-Irwin Inlet 1:250,000 sheet offered us a new challenge in the form of the Proterozoic Albany-Fraser Province that both terminated and reworked the southern margin of the Yilgarn Craton. However, that can wait for the "Albany-Fraser Retrospective"!

While the ancient high-grade rocks of the southwestern Yilgarn were being mapped, the late Ian R. Williams was mapping in the Narryer region of the northwest Yilgarn, and finding high-grade metasedimentary rocks with similarities to those in the southwest. Ian and I discussed our findings and proposed a joint investigation, with the plan being to present the results at the 1980 Archean Symposium. However, this was the era of mapping the state at 1:250,000 at all cost, so it fell upon deaf ears. It was not until I left the GSWA in June 1981 to join the Western Australian Institute of Technology (WAIT - later Curtin University) that I had the opportunity to work there.

Fresh with the knowledge encapsulated in the Gee at al. (1982) paper, which we had just revised following review, it was clear to me that the outstanding issue in the western Yilgarn Craton was to find out why five greenstone belts (four at low metamorphic grade) were present in the high-grade 'Western Gneiss Terrain'. This became the topic of the first ARC Large Grant of Wilde and Pidgeon (Bob Pidgeon having joined WAIT six months after me). With that grant, Bob was able to set up U-Pb dating in Perth – forming the basis of the excellent suite of geochronological equipment that is currently housed in the John de Laeter Centre for Isotope Research. Saddleback was the first target, with an age of ~2670 Ma (Wilde and Pidgeon, 1986), followed by Wongan Hills, with an age of ~3000 Ma (although this was higher grade, it was a greenstone belt – Pidgeon et al., 1990). Importantly, it allowed us to identify two ages of greenstone belts along the western margin of the Yilgarn Craton, which we extended into the Murchison Province to the east (Pidgeon et al., 1988). We then went to Tallering and Twin Peaks – and eventually to Jack Hills, the largest of the 'greenstone belts' and also the least understood. I should point out here that a new commodity, already identified years before by Western Mining, was present in the western Yilgarn – iron ore. Reserves were in place over Archean banded iron-formations at Tallering Peaks and Jack Hills, with both areas subsequently being mined in the new millennium.

I have told the history behind the Jack Hills investigations elsewhere (Wilde, 2010); this is a truncated version. Over two field seasons, 3rd year students from WAIT mapped the whole belt and its surrounding granitoids at 1:10,000 scale, under the supervision of John Baxter, Bob Pidgeon and myself. We collected a series of granitoid and metasedimentary samples, including one from a prominent exposure of conglomerate on the eastern flank of Eranondoo Hill. As we were well aware of the exciting discovery of ancient rocks and zircons from Mt Narryer, some 60 km to the southwest, we were optimistic that Hadean zircons might also be present at Jack Hills; with the conglomerate likely to contain the oldest material. After some lobbying, the first zircons from the conglomerate (sample W74) were run on SHRIMP I at the ANU and immediately hit the jackpot – two zircons with an age of 4276±12 Ma were identified (Compston and Pidgeon, 1986), making these the oldest known portions of the Earth's crust. Subsequent studies were undertaken and more information collected, but nothing older was found. However, advances in technology enabled additional techniques to be applied, including the measurement of oxygen isotopes in single zircon grains. Following a meeting in Beijing with Prof John Valley from the University of Wisconsin, I returned to the original vials of zircon and prepared two mounts so that his PhD student (William Peck) could obtain oxygen isotope data from a suite of grains that spanned over 1 billion years of Earth's history. The first mount contained few Hadean grains, so I ran the second. As I only needed to identify >4 Ga grains, I set the Curtin SHRIMP to run single cycle analyses during which time I did a rough calculation of the $^{207}Pb/^{206}Pb$ ratio, providing a back-of-the-envelope estimate of the age. Then another jackpot – one quite innocuous-looking grain recorded an age of ~4.4 Ga. So I ran a complete analysis, where it gave an age of 4363±8 Ma. Following oxygen isotope analysis at the University of Edinburgh, I repolished the mount and undertook more U-Pb analyses on the grain of interest, with the specific aim of avoiding any imperfections. One part of the grain that became enlarged following the polishing this time yielded an age of 4404±8 Ma, making this well-and-truly the oldest identified portion of the Earth's crust (Wilde et al., 2001) – and it remains so today.

Thus the western Yilgarn Craton has not only provided a wide range of important mineral commodities - especially gold, bauxite, tin-tantalum-lithium, iron ore and coal - but has also become internationally known as the most significant region in the world for Hadean zircons and their application to early Earth studies. Not bad for a region that was largely ignored for decades.

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Biography

SIMON WILDE is Professor of Precambrian Geology in the Department of Applied Geology at Curtin University and a John Curtin Distinguished Professor. He commenced his career at the Geological Survey of Western Australia in 1972, where he mapped and compiled the Perth, Pinjarra, Collie and Pemberton-Irwin River 1:250,000 Sheets. In 1981, he joined Curtin University (then the Western Australian Institute of Technology) where he has remained ever since. Career highlights include the discovery of the Saddleback Greenstone belt that hosts the Boddington gold deposit, the identification of the oldest known portion of the Earth's crust (4,404 Ma zircon from the Jack Hills conglomerate) and is co-author of the widely-accepted model for the evolution of the North China Craton. He has worked in China since 1991, publishing over 150 research papers, and is an adjunct/visiting professor at four major universities/research institutes there. He is a Thomson-Reuters Highly-Cited Researcher, being in the top-ten globally by citations, and is currently Australia's most highly-cited geoscientist.

What REALLY Mattered Then and What REALLY Matters Now

ROY WOODALL[1]

Western Mining Corporation (WMC) commenced science-based exploration on the Yilgarn Craton in 1934. It struggled for 21 years as a gold producer until 1954. Despite only modest success at Norseman, it continued, committed to using the geological sciences; geology, geophysics and geochemistry! From its exploration experience can be distilled the factors that REALLY matter. Ultimately its exploration was extraordinarily successful!

This retrospection relates entirely to the period 1958 to 1995. No company has devoted more exploration resources to the Yilgarn Craton; no company was more successful: 62 economic discoveries, including 3 giant mineral camps (Schodde, 2014).

1950s

In 1954 a small struggling, gold mining company found the best bauxite deposit in the world, a deposit ignored by others because it was thought "low-grade". High in silica, yes, but the silica was mainly as inert quartz, not clays. Another benefit was that the aluminium-bearing mineral was gibbsite, not boehmite. Science and scientists REALLY mattered.

1960s

Kambalda

On the road to discovery the factors that REALLY matter are often few. Consider for example the discovery of the Kambalda Nickel Camp with a pre-mined resource (as at 31 May 2014) of 60.2 million tonnes @ 3.08% Ni (Schodde, 2014).

A small ironstone outcrop, a prospector or two, a Kalgoorlie School of Mines lecturer all mattered - but not critically! It was the availability of semi-qualitative emission spectrography which confirmed the presence of nickel and copper (0.1 to 1%), molybdenum (0.01 to 0.1%), tellurium (0.001 to 0.01%) and silver (0.0001 to 0.001%), determined by AMDL on 17 September 1964, that REALLY mattered!

V.M. Goldschmidt, and his book Geochemistry REALLY mattered. He had this to say about those trace elements:

Concerning silver: *"silver should be preferentially connected with gabbroid magmas"*. Such magmas were known to be associated with nickel sulphide ores in Canada.

Concerning molybdenum: *"small amounts of molybdenite are sometimes found in genetic relationship to basic gabbroid magmas.... where it is a minor constituent of pyrrhotite-pentlandite-chalcopyrite ores"*. Pentlandite is the main ore mineral of nickel sulphide ores.

Concerning tellurium: *"The element is present in significant amounts in pyrrhotite magmas together with pentlandite and chalcopyrite"*. (Goldschmidt, 1954).

On 23 September, 1964, the Directors were advised as follows:

"The four samples the prospector brought averaged 0.9% Ni and a sample I sent to AMDL for complete spectrographic analysis showed about 0.5% Cu as well as nickel, but ALSO, abnormal molybdenum and tellurium (each at least 100 times normal) and a very faint trace (0.0001 - 0.001%) silver. The occurrence is of great interest! It confirms my belief that the country is not prospected for base metals" (Woodall, 1964a).

Five days later, on September 28, 1964, the Directors were advised:

"The nickel-copper content of the primary sulphide ore can only be guessed, but is likely to be higher than the gossan which is well leached. A thorough reconnaissance of the area is warranted as other gossan outcrops may occur. Geological mapping of the area may also define the control of the lode already found, and show-up extensions.

I could achieve something useful if I could use two geological students in the area during the summer vacation period. The cost of a 3 month programme would be about £2,000" (about $50,000 in 2015 terms)(Woodall, 1964b).

This information was tabled at a WMC Board Meeting on 26 January, 1965 (Australia Day), and the Directors' response REALLY mattered. As cash-poor as WMC was, the Directors made a bold statement:

Red Hill

If the assessment of the surface geology now being undertaken indicates that further work should be carried out, the principle of Western Mining Corporation doing this itself has been accepted but before work starts a report and request for an allocation of funds should be submitted. (Minutes of WMC Board Meeting 24.1.65 WMC Document M/341/p).

1. *Corresponding author:* Roy Woodall

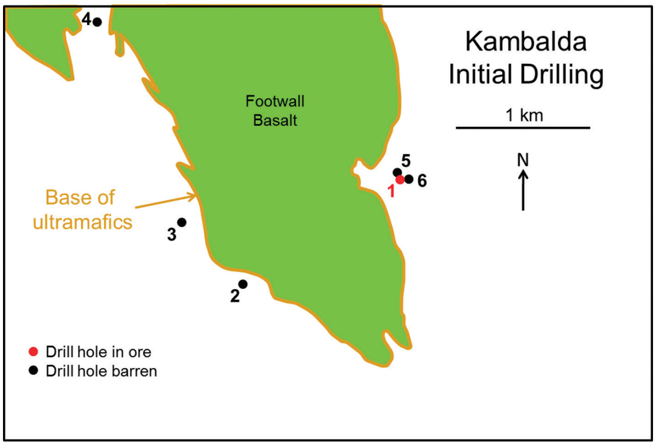

Figure 1. First six holes drilled at Kambalda

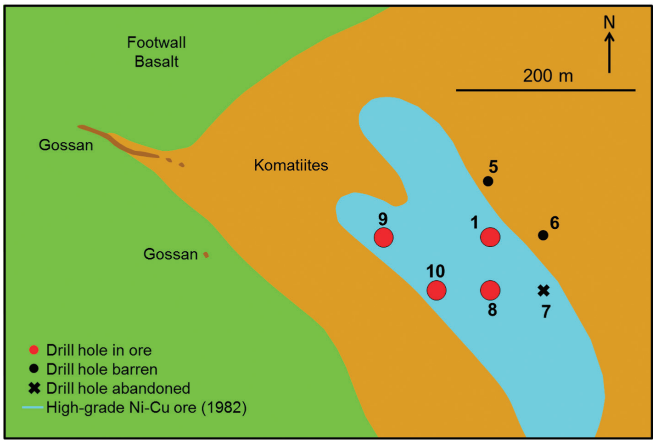

Figure 2. Subsequent drill holes define Lunnon shoot

Despite 70 years of prospecting and mining on the Yilgarn Craton, no nickel-copper mineralisation had ever been found, nor anywhere in the world in Archean rocks. This Board directive was an astonishing demonstration of the Directors' confidence in science. The Company had persevered for 32 difficult years, determined to never abandon its fundamental strategy. Confidence in science had been helped by the scientific advice the Directors had received, about "low-grade" laterites in the Darling Ranges in Western Australia. They were now known to be the "richest" bauxites in the world and had attracted finance from a major US company, Alcoa.

On 20 April, 1965, the Directors were advised of the result of geological mapping, which, incidentally, had been in progress south of Kalgoorlie since 1961, and by 1964 had almost reached Red Hill. The mapping was rapidly extended, and the results REALLY mattered.

"We have now established that the nickeliferous gossan reported from Red Hill (my memo 2809/64) occurs at the base of an ultra-basic sill which in turn overlies basaltic lavas.... The extent of the lower contact of the ultrabasic sill defines a domal structure and outcrops for a distance of approximately 13 miles... Much of the contact is completely concealed.

The only practical way to find out the nickel-copper content of the sulphide minerals below the gossan is to drill the contact below the level of weathering at a number of localities. Probably five or six holes will be required. Total cost approximately £11,500." (Woodall, 1965).

The first drill hole intersected a contact between ultramafics and underlying basalt, identical to the geology at the gossan outcrop, but the contact was barren. Then something else happened that REALLY mattered. The geologist in-charge, Dick Elkington, who had had experience with nickel exploration in Canada, used his experience to tell the driller to drill on! An intersection of massive sulphides resulted, the assay being 8.3% nickel from 478 ft to 487 ft.

But, real stress followed! Of the next five drill holes, four were barren, including two close to the discovery hole (Figure 1); and one drill hole, distant from the discovery hole, intersected only a narrow stringer of sulphide. Then something also occurred that REALLY mattered. The six drill holes were completed but no directive was issued to terminate the program, and just-as-well, for three of the next four holes were as good as the first. The Lunnon orebody had been discovered (Figure 2). Rather than the project being abandoned, it launched the discovery of the great nickel sulphide potential of the Yilgarn Craton, and a scientific bonus, the discovery of super-hot komatiite lavas that had erupted on to an Archaean seafloor.

What REALLY mattered: Science, Scientists, and a Board of Directors who trusted their Scientists!

Yeelirrie

Then followed a second economic discovery and again, a world-first; the Yeelirrie uranium deposit, in a concealed, Tertiary river channel! Again, science and smart scientists REALLY mattered! And, when the time came, in 1975/76, to drill for copper on the Gawler Craton in South Australia, in the desert, beneath 300m-plus of barren sediments, the first nine holes failed to find an ore deposit. But neither senior management nor any Director asked for such a "wildcat" expensive program to be terminated! Then the tenth hole found the giant Olympic Dam deposit, also a world-first. Science, scientists and Directors who were interested in science and who had learnt to trust their scientists REALLY mattered.

Recruitment

Successful mineral and petroleum exploration depends on recruitment, and that recruitment policy REALLY matters. From 1950 to 1995 recruitment was managed by scientists. For many years as Exploration Manager and later as Director of Exploration, I sometimes spent a third of my time visiting universities to seek bright young scientists and to identify universities to which selected WMC geoscientists should be sent on study-leave. The Human Resources department had no authority over these important Exploration Division activities! How can non-scientists assess scientists?

Ore Deposit Documentation

We have a profound responsibility to scientifically document the ore deposits we are mining and therefore destroying! That documentation must be of the highest scientific integrity, and long term. Consider the giant, unique, copper-uranium-gold deposit; the Olympic Dam deposit. The scientific documentation has been the responsibility of a dedicated scientist, Dr Kathy Ehrig since 1992. In her wisdom, and commitment to the highest possible level of science and the scientific integrity of scientific literature, she has only just begun to publish the results of over 20 years of research. Meanwhile, since the discovery of the deposit in 1976, many papers have been published describing the deposit but based on limited sampling. Common sense would predict that publications based on such sampling and short-term studies risk scientific integrity!

There is a lesson in all this. The scientific documentation of any ore deposits is not a short-term task, especially for major deposits. What REALLY matters is commitment to long-term scientific integrity!

The study of the largest of the Yilgarn Craton's gold deposits, the Golden Mile gold-silver-telluride deposit, has created 250 publications since 1971, but how many have scientific integrity? How many have been written by scientists who had long periods of contact with the deposit? Not many I fear! What is encouraging is the work of John Clout, from 1980 to 1992, and the current KCGM team.

John Clout studied the Golden Mile deposit for 12 years. Extracts from the Summary of his PhD thesis are, to say the least, illuminating!

"Combined structural, alteration, fluid inclusion and stable isotope studies all support a shallow crustal setting for the deposit consistent with an 'epithermal' genetic classification for the deposit. Data from each of these studies is inconsistent with previous metamorphic/ductile shear zone models for the deposit.

Fluid phase separation (occurred) at temperatures largely between 170 and 250°C and pressures ranging from less than 10MPa (hydrodynamic) to 26MPa (lithostatic ≈ 1000m).

....

The Golden Mile hydrothermal alteration is considered to have resulted from the convection of surface fluids and precious metal-bearing magmatic fluids above and surrounding shallow level syn-volcanic intrusive porphyries during rapid uplift and erosion of the greenstone pipe." (Clout, 1989)

The current research by the KCGM team, led by David Nixon for 15 years, suggests complete agreement with John Clout.

"Re-mapping of the Fimiston Superpit agrees with this interpretation of the geology for the Golden Mile. The bulk of the mineralisation in the Kalgoorlie Camp (Fimiston style mineralisation) is interpreted to have formed early, at a shallow level, in an active and dynamic tectonic environment."

Has the research centred on Kalgoorlie's Golden Mile, for so many decades, been deficient, and if so, was it due to the lack of integrity of the sampling on which the research was based? What is exciting about the research of Clout and the current KCGM geoscience team is that the formation of this giant orebody was a shallow crustal event, i.e. neither deep crustal, nor metamorphic.

The early geological history of a wide band of the Yilgarn Craton from Norseman to Wiluna and beyond involved an Archaean sea and super-hot ultramafic lavas pouring out on the seafloor. There was thermal erosion of the seafloor and the formation of nickel sulphide deposits. At Kalgoorlie, after a brief moment of geological time, one of the world's great gold deposits formed on or close to the same seafloor! Komatiitic nickel sulphide deposits stretch from Norseman to Wiluna; why not epithermal gold deposits? The giant Golden Mile deposit outcropped, but for several years was not recognised as a significant gold deposit; remember that once-upon-a-time everyone thought it was crazy to look for nickel sulphide ore deposits in the Yilgarn Craton!

Another recent, and highly commendable research project in the Kalgoorlie region is that of Gerard Tripp (Tripp, 2013). He has documented and correlated the stratigraphy of four domains in the Eastern Goldfields, a project which has taken 15 years. Long-term commitments are to be complimented and are what high quality research requires – they REALLY matter.

What REALLY matters now?

Surprise, surprise; it is

- Science
- Scientists
- Directors interested in science who trust their scientists, and are committed to persevere with science-based exploration.
- Recruitment and personnel management by scientists
- Documentation of ore deposits must be based on adequate sampling and a long- term commitment

Why are all these factors believable? Because, over 40 years they transformed a small struggling gold miner to a company which, by 1996, was generating $3.7 billion of net revenue ($5.8 billion in 2015 terms)! (Figure 3).

Trouble awaits a company when Directors and Senior Management ignore science and its scientists and rely solely on Rate of Return (ROR) when making decisions. ROR decisions are short-term.

Oh yes, there is something else that REALLY matters. Big ore deposits make the most money. Big ore deposits need big plumbing systems because the formation of big ore deposits needs great volumes of fluids. Big plumbing

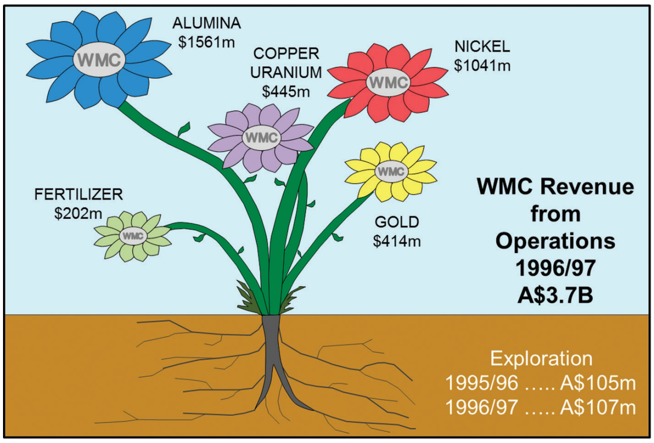

Figure 3. Growth of WMC. $3.7 b in 1996/97 is equivalent to $5.8 b in 2015 terms

systems occur on major, continental, steep structures, especially where two intersect. This REALLY matters now, just as it REALLY mattered 1950 to 2000 during Tim O'Driscoll's life-long research (O'Driscoll, 2007).

3D Seismic technology also REALLY matters now. It has transformed petroleum exploration and is effective in areas of crystalline rocks. It is now possible to map steep structures which cannot be imaged with 2D seismic technology.

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Biography

ROY WOODALL has had a long and distinguished career as an exploration geologist. After graduating from the University of Western Australia in 1953 with BSc(Hons), he joined Western Mining Corporation Limited and embarked on a career with that company that spanned 48 years. He started as a field geologist and finished as a Director of WMC, a position he held for 25 years. Early in his career he took study leave and completed a Masters degree in Mining at the University of California, starting an in-career training practice that benefitted many WMC geologists. During his tenure, he and his geological team were credited with a remarkable discovery record which included Darling Range bauxite, Kambalda nickel, Yeelirrie uranium, and the massive Olympic Dam Cu-Au-U deposit.

Roy has received numerous honours and awards and has served on many advisory committees. He was made an Officer of the Order of Australia in 1981, and other awards included the William Smith Medal (Geological Society, London), The Institute Medal (AusIMM), Mawson Medal (Australian Academy of Science) and an Honorary Degree of Doctor of Science from UWA. Committee positions have included Member of the Australian Science and Technology Council, Australian Geological Survey Organisation Advisory Committee (previously Bureau of Mineral Resources) and the Council of the Australian Mineral Foundation.

The Yilgarn: Where we are in 2015

STEPHEN WYCHE[1]

Introduction

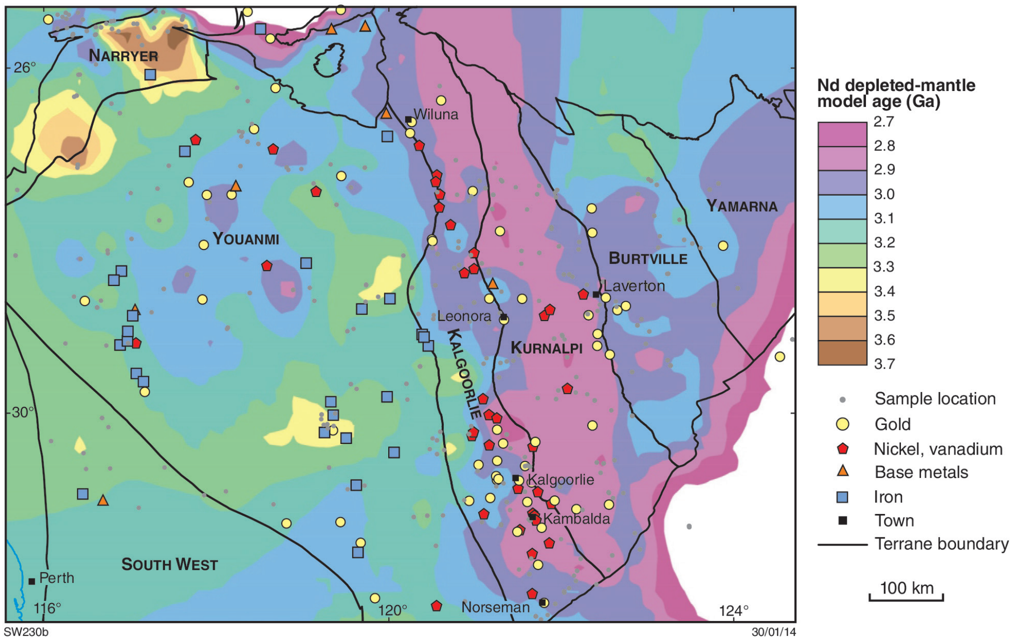

Figure 1. Nd depleted-mantle model age map for the Yilgarn Craton showing terrane subdivisions and locations of major mineral deposits (modified from Champion and Cassidy, 2007).

The Paleoarchean to Neoarchean Yilgarn Craton hosts world-class deposits of gold and nickel, and significant iron and volcanic-hosted massive sulfide (VHMS) base-metal deposits. Economic iron deposits are confined to the western part of the craton. Acquisition of a variety of new datasets across the craton over the past 20 years has led to major advances in the understanding of the geological evolution of the craton at all scales. These new datasets include large amounts of SHRIMP U–Pb zircon geochronology (e.g. Kositcin et al., 2008; GSWA, 2015), new geophysical data including aeromagnetics, gravity, passive seismic, deep-crustal seismic reflection and magnetotelluric (MT) data (e.g. Goleby et al., 2003; Wyche et al., 2013), regional geochemical data (e.g. Cassidy et al., 2002), and regional isotopic data (e.g. Wyche et al., 2012; Champion, 2013). This new understanding has encouraged the application of the holistic mineral systems approach to mineral exploration as a tool for developing targeting criteria, particularly for nickel and gold (Blewett et al., 2010a; McCuaig et al., 2010).

Components

Cassidy et al. (2006) divided the Yilgarn Craton into terranes defined on the basis of distinct sedimentary and magmatic associations, geochemistry, and ages of volcanism (Fig. 1). The Narryer and South West Terranes in the west are dominated by granite and granitic gneiss with minor supracrustal greenstone inliers, whereas the Youanmi Terrane and the Eastern Goldfields Superterrane contain substantial greenstone belts separated by granite and granitic gneiss. The Eastern Goldfields Superterrane comprises the Kalgoorlie, Kurnalpi, Burtville and Yamarna Terranes.

The Ida Fault (Fig. 1), which marks the boundary between the western Yilgarn Craton and the Eastern Goldfields Superterrane, is a major structure that extends to the base of the crust. Various geophysical techniques, including deep-crustal seismic, seismic receiver-function analysis, and MT surveys, show the Yilgarn crust to be between 32 and 46 km thick, with the shallowest Moho beneath the Youanmi Terrane. The crust is thicker in the southwest, and thickest in the eastern part of the Eastern Goldfields Superterrane. Seismic and gravity data suggest that the greenstones are 2–7 km thick (Wyche et al., 2013).

Isotopic data, including Sm–Nd (Fig. 1; Champion and Cassidy, 2007) and Lu–Hf (e.g. Wyche et al., 2012) data,

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show that the terrane subdivisions of the Yilgarn Craton reflect regions with distinctive crustal histories. The Narryer Terrane, which contains both the oldest detrital zircons yet found on Earth (back to c. 4400 Ma: Wilde et al., 2001) and the oldest rocks in Australia (back to c. 3730 Ma: Kinny et al., 1988), shows abundant evidence of very old model ages. The Youanmi Terrane has a more mixed history, whereas the Eastern Goldfields Superterrane contains some distinctly more juvenile components than the terranes to the west.

The Rocks

The supracrustal rock record in the Yilgarn Craton dates back to at least c. 3080 Ma in the Youanmi and Narryer terranes in the west (Rasmussen et al., 2010) and c. 2960 Ma in the Burtville Terrane in the northeast. However, rocks that formed after c. 2820 Ma dominate greenstone successions across most of the craton.

In the central Youanmi Terrane, a cycle of mafic–ultramafic to felsic volcanism between c. 2820 and 2735 Ma is attributed to a major plume that produced large mafic–ultramafic layered intrusions between c. 2820 and 2800 Ma (Ivanic et al., 2010), coincident with similar, but less voluminous, magmatism in the eastern part of the craton (Wyche et al., 2012). This event may have resulted in partial break-up of the early Yilgarn Craton with rifting in the east (Czarnota et al., 2010) and incipient rifting marked by younger Nd model ages and the layered intrusions in the central Youanmi Terrane. A protracted period of mafic to felsic volcanism and associated sedimentation continued from c. 2800 Ma until c. 2735 Ma (Van Kranendonk et al., 2013). Dominantly calc-alkaline volcanism after c. 2760 Ma broadly coincided with a period of mafic tonalite–trondhjemite–granodiorite (TTG) and enriched high-field-strength element (HFSE) granite magmatism (Cassidy et al., 2002).

The last recognized regional greenstone-forming event in the Youanmi Terrane was a mafic to felsic volcanic cycle between c. 2740 and 2720 Ma (Van Kranendonk et al., 2013), which was contemporaneous with high-Ca TTG and high-HFSE granite magmatism (Cassidy et al., 2002).

Except for rare greenstones in the South West Terrane, after c. 2715 Ma volcanic activity and greenstone development in the Yilgarn Craton was restricted to the Eastern Goldfields Superterrane. Andesite-dominated calc-alkaline volcanism in the eastern Kurnalpi Terrane (Barley et al., 2008) and dacitic volcanism in the northern Kalgoorlie Terrane were prevalent between c. 2715 and 2705 Ma (Kositcin et al., 2008).

In the Eastern Goldfields Superterrane, a mooted plume event at c. 2700 Ma (Barnes et al., 2012) produced voluminous komatiites, which occur as both flows and high-level intrusions (e.g. Trofimovs et al., 2004). They are preserved in a distinct north-northwesterly trending belt, about 600 km long and up to 100 km wide, between Norseman and Wiluna (Fig. 1). The mafic–ultramafic succession, which also contains tholeiitic and komatiitic basalt, is well constrained in age to between c. 2710 Ma and 2692 Ma (Kositcin et al., 2008) and partly overlaps in age with the andesite-dominated calc-alkaline volcanism.

Between c. 2692 and 2680 Ma, volcanic centres in the western part of the Kurnalpi Terrane produced bimodal (basalt–rhyolite) volcanic and associated intrusive and sedimentary rocks (Barley et al., 2008), coinciding with the main period of high-HFSE granite magmatism (Cassidy et al., 2002). This volcanism, which locally hosts VHMS mineralization, overlapped in age with, and was succeeded by, TTG magmatism and associated sedimentary rocks and mafic intrusions represented by the Black Flag Group in the Kalgoorlie Terrane. The deposition of the Black Flag Group between c. 2690 and 2660 Ma coincided with voluminous high-Ca TTG granite magmatism in the Eastern Goldfields Superterrane.

The youngest supracrustal successions in the Yilgarn Craton are the so-called 'late basins', which rest unconformably on all earlier greenstones in the Eastern Goldfields Superterrane. Likely deposited in a relatively short time (10 m.y.) after c. 2665 Ma, they preserve fluvial and deep-marine facies (Krapež et al., 2008).

The latest period of granite emplacement, after c. 2655 Ma, consisted of widespread low-Ca granite without contemporaneous greenstone deposition. A distinctive belt of alkaline granites, emplaced at this time, appears to coincide with deeply penetrating crustal structures and is mainly restricted to the Kurnalpi Terrane (Smithies and Champion, 1999).

Deformation

Deformation histories have been described for the various terranes that comprise the Yilgarn Craton (Blewett et al. 2010b; Wyche et al., 2013). Although there are many common elements, particular regions are characterized by deformation that reflects their overall magmatic and tectonic history.

Large-scale Crustal Structure and Mineral Distribution

Begg et al. (2010) and Barnes et al. (2012) suggested that the komatiite distribution in the Eastern Goldfields is controlled by the presence of older blocks within the craton, which are underlain by thick subcontinental lithospheric mantle (SCLM). New Lu–Hf data suggest the presence of other pro-cratonic blocks in the Youanmi Terrane (Mole et al., 2014). The areas of juvenile crust adjacent to these proto-cratonic blocks host the major gold and nickel deposits of the Yilgarn Craton. Some VHMS deposits (e.g. Jaguar–Bentley in the Eastern Goldfields) occur within the juvenile zones, but deposits in older successions, such as Golden Grove, have more cryptic settings (Hollis et al., 2014). All economic iron deposits lie in areas of old, reworked crust.

Gold mineralization systems in the Eastern Goldfields Superterrane have been studied extensively over the past 15 years. Blewett et al. (2010a,b) described the key elements in the architecture that play a role in the localization of gold deposits. In particular, they recognized that crust-penetrating shear zones are potentially important pathways for fluids, but that not all apparently prominent structures penetrate deeply into the crust. Blewett et al. (2010b) suggested that the best endowed areas are those that have a long history of structural preparation through repeated deformation, perhaps back to the earliest basin-forming events (e.g. Miller et al., 2010). In these places, there are likely to have been multiple episodes of mineralization. The largest gold deposits appear to be related to structures that were able to directly access deeply penetrating structures in relatively juvenile crust. These structures are broadly contemporaneous with TTG-style granites (Wyche et al., 2013).

The Youanmi Terrane includes several distinct crustal elements, which are clearly delineated on the Yilgarn Nd model-age map (Fig. 1). Immediately west of the Ida Fault, the Nd model-age map shows old, reworked crust. In the centre of the terrane, a structural corridor, which is occupied by greenstones of the Murchison Supergroup and associated granites, is highlighted by the presence of more juvenile crust (Van Kranendonk et al., 2013). This corridor contains the most well-endowed gold deposits, as well as large layered mafic–ultramafic igneous complexes that host vanadium and minor PGE mineralization. West of the corridor, old, reworked crust is similar in character to that east of the corridor.

Newly acquired, large-scale datasets provide insights into the distribution of known mineralization in the Yilgarn Craton, and a focus for targeting future discoveries in less well explored areas and under cover.

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Biography

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