North Pilbara National Geoscience Mapping Accord project (1995–2000)

Scientific highlights

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AGSO and the Geological Survey of Western Australia (GSWA) conducted a multidisciplinary project in the North Pilbara region under the National Geoscience Mapping Accord (NGMA) between 1995 and 2000. The research was driven by a need to ascertain whether exploration- and mineral-deposit models based upon late Archaean examples were suitable for older Archaean terranes. The goal was to document differences between late Archaean and the early to mid-Archaean mineral systems, and then develop regional thematic synthesis datasets to construct more robust models for the entire Archaean era.

This paper highlights the diversity of the Pilbara's mineral systems, discusses exploration tools used to map alteration haloes, considers geochemistry and crustal provenance, explores the 3D geometry of the granitoid–greenstone terrane, and promotes the regional synthesis and GIS, which assist exploration in the Pilbara and other Precambrian terranes.

The Archaean Pilbara Craton is an ovoid entity 600 kilometres by 550 kilometres located in the north-west part of Western Australia. The North Pilbara region represents the mostly exposed northern 25 per cent of this craton. The rest is concealed by late Archaean and 'younger' cover rocks. The Pilbara Craton is a granitoid–greenstone terrane characterised by a distinctive, and relatively intact, ovoid pattern of granitoid batholiths (50–120 km diameter) and enveloping greenstones. Crustal-scale shear zones are limited to the central and western part of the North Pilbara region. The craton's tectonic history spans 800 million years (3.65 to 2.85 Ga). Much of the crustal growth occurred in a series of tectono-thermal events made up of repeated cycles of granitoid magmatism and greenstone volcanism, followed by deformation and metamorphism. The Pilbara Craton has a great diversity of mineral deposits. It hosts some of the world's oldest mineral systems of their type, many of which were active more than once. The oldest systems include: syngenetic barite (3490 Ma), VHMS base metals (3460 Ma, 3240 Ma, 3125 Ma, 2950 Ma), lode Au±Sb (3400–3300 Ma, 2900 Ma), porphyry Cu-Mo (3320 Ma), komatiite-hosted Ni-Cu (>3270 Ma), layered mafic-ultramafic complex-hosted V or Ni-Cu-PGE (2925 Ma), pegmatite Sn-Ta (2850 Ma) and epithermal Au (3450 Ma?, 2760 Ma).

Archaean mineral systems

Table 1 lists a number of fundamental tectonic and metallogenic differences between the granitoid–greenstone terranes of the Pilbara Craton (3.65–2.8 Ga) and highly mineralised Neoarchaean provinces such as the Eastern Goldfields in Western Australia or the Abitibi in Canada. Several major differences are apparent, the most significant of which is possibly the duration of crustal growth. Both the Abitibi and the Eastern Goldfields grew over relatively short periods of less than 200 million years, compared with the Pilbara Craton's development over more than 800 million years. There is extensive crustal recycling in the Pilbara Craton because of this long history of crustal growth. Other important differences between the North Pilbara and Neoarchaean terranes are the shape and depth extent of the granite complexes and greenstone belts (table 1). More importantly though, in terms of mineral systems, is the extent of shear zones. The Pilbara Craton has few province-scale shear zones, whereas major shear zones in the Eastern Goldfields and Abitibi provinces commonly extend more than 200 kilometres.

These differences in tectonic development may have had a direct bearing on the mineral endowment of the North Pilbara region. For instance, protracted crustal growth may have been a two-edged sword. It probably is responsible in part for the diversity of mineral systems, but slow growth may have hampered the development of large ones. Rapid growth from magmatic and volcanic events in the Abitibi and Eastern Goldfields provinces produced a lot of heat over a short time, facilitating the development of large mineral systems. In contrast, slow growth in the Pilbara may have facilitated a large variety of different mineral systems, but the rate of heat production was probably too low to drive enough fluid to form large mineral systems. The major metallogenic epoch in the North Pilbara Craton was the development of the Central Pilbara Tectonic Zone, an event that introduced a relatively large amount of heat into the crust in a short time (<100 Ma).

A second factor that may have hampered development of large mineral systems is the lack of large-scale shear zones. The longest shear system in the North Pilbara, the Sholl Shear Zone, is exposed over only 200 kilometres. Major shear zones in the Eastern Goldfields and Abitibi provinces are typically longer than 200 kilometres, and some exceed 500 kilometres. Long shear systems may facilitate large mineral systems by allowing fluid circulation in an extended part of the Earth's crust.

New potential, old province

The perception that the Pilbara is well exposed and therefore all mineral deposits have been discovered is ill-founded. Less than 25 per cent of the craton is exposed and, even in areas of exposure, new mineral systems have been recently found (e.g., the well-preserved, high-level Archaean epithermal gold systems[1]), which has resulted in new ground uptake and investment in the Pilbara.

Table 1. Comparison of the Pilbara Craton with highly mineralised Neoarchaean provinces

	Pilbara Craton	Eastern Goldfields, Superior provinces	Comments
Crustal growth	Extensive recycling of crust by many events over a long period	Major crustal growth event in a short period	
Granite geometry	Domal and ovoid geometry	Elongate geometry	
Greenstone geometry	Greenstones (and granitoids) extend to 14-km depth.	Greenstones extend to 5–7 km where they are underlain by low-angle detachments and deep tapping shear zones.	
Shear zones	Craton-scale shear zones are not common. With few exceptions (e.g., Sholl and Mallina Shear Zones), shear zones are local features.	Craton-scale shear zones are common. These shear zones are first-order controls on lode gold deposits.	
Crustal level exposed	Mostly greenschist facies metamorphism. Local amphibolite facies (LP-HT) in greenstones near granitoids, local kyanite-bearing suggests some higher pressure.	Mostly greenschist facies metamorphism in greenstones. Local amphibolite facies in greenstones near granitoids. In the Eastern Goldfields there are extensive gneiss belts in 'external' granites.	Extensive gneisses in the Eastern Goldfields may imply deeper crustal levels and therefore larger throws on greenstone-bounding faults and shear zones.
Diversity of mineral systems	Atypical Archaean deposits such as Sn-Ta pegmatites, porphyry Mo-Cu deposits and epithermal Au are common in the Pilbara. More 'typical' deposit types are also present.	Characterised by 'typical' Archaean deposits like lode Au, VHMS (Abitibi) and komatiite-hosted Ni-Cu. VHMS not common in EGP.	Many deposit types present in the North Pilbara Terrane are more typical of Proterozoic or Phanerozoic terranes.
Size of mineral systems	Many different mineral systems operated, but the associated mineral deposits tend to be small, and total endowment is apparently small.	Relatively few mineral systems operated, but they produced much larger deposits (e.g., lode Au and VHMS) and a very high endowment.	
Temporal distribution of mineralising events	Episodic mineralising events over a period of 800 Ma (e.g., 4 VHMS events and 2 orogenic gold events)	Single, global(?) events (e.g., 2710±20 Ma for VHMS and 2630±10 Ma for orogenic gold)	
VHMS deposits	Significant Pb and baryte; some deposits in calc-alkaline settings.	Generally lack Pb; always lack baryte; mainly in tholeiitic settings.	Pilbara characteristics are more like Phanerozoic systems.

Extensive areas of the North Pilbara are presently exposed close to the (ca. 2775 Ma) Hamersley Province unconformity surface.[2] This exceptional preservation significantly improves younger mineralising events of gold and possibly diamonds in the mostly older mid-Archaean Pilbara granite–greenstone terrane. Areas of high-level (epithermal) systems preserved in the west and far east Pilbara have been documented by the NGMA project. The systems are interpreted as being related to NNW-trending dextral faults and associated relay movements during the early stages of the Hamersley Province extensional event. Epithermal veins cut the (ca. 2765 Ma) Opaline Well Granite, and similarly aged Gregory Range Granite.

Application of exploration tools

The North Pilbara project has had significant success in developing and applying exploration tools for the Pilbara and other provinces. Most of the project's effort focused on mapping alteration systems in both well-exposed and poorly exposed

regions. Successful techniques include the HYMAP multispectral scanner, airborne gamma-ray spectrometrics, oxygen isotopes, and whole-rock geochemical depletion patterns.

HYMAP, an airborne 128 channel multispectral scanner, was flown over two 20-kilometre-long by five-kilometre-wide strips in the Mallina–Indee area of the Pilbara.[3] The HYMAP data successfully mapped alteration minerals such as pyrophyllite and sericite, distinguished Fe-chlorite from Mg-chlorite, and separated dolomite from calcite in calcrete. Resultant images are presented as image abundance maps with a 10-metre pixel cell size. Several sericite-pyrophyllite targets generated from the HYMAP images produced anomalous gold on subsequent analysis,[3] demonstrating the predictive value of this tool. This work has featured widely as an excellent example of the application of remote sensing as a mapping tool in regolith-dominated areas.

Work in the Panorama volcanic-hosted massive sulphide (VHMS) district generated reliable vectors to ore by using oxygen isotopes, converting these to palaeotemperatures, and locating circulation and discharge cells in subvolcanic intrusions.[4] The calculated temperatures not only define fluid pathways, but may predict Zn/Cu rations in VHMS deposits.

In the same VHMS mineralising system, whole-rock geochemistry was also used as a mapping tool. District-scale depletion of Zn and Cu has been mapped, and these depletion zones define fluid pathways.[5] These data, with mass balance calculations, indicate that Zn, Cu, Pb, Mo, Ba and S could have been entirely derived from the volcanic pile, and that a magmatic-hydrothermal source is not required.[5,6]

To date, most users of gamma-ray spectrometric data have generated standard red-green-blue images for their interpretation. But AGSO applied a number of data processing techniques. The enormous dynamic range of the data involved large areas of over-saturation (white) from K-U-Th-rich granites, and equally large areas of undersaturation (black) from mafic and ultramafic rocks.[7] Dose counts were converted to ppm U and Th and % K, and used to generate 'chemical' maps that closely matched traditional lithological maps. These images highlighted areas of mapping discrepancy—a result of error or changed rock chemistry (alteration). Images of the K, Th, U principal components were developed, and used to define evolutionary paths for the granitoid complexes.[7]

Simple K/Th ratios were used to map K-depletion anomalies associated with the Panorama alteration system.[8] These anomalies map the same interpreted fluid pathways in the VHMS system determined from whole-rock chemistry[5,6] and oxygen isotopes[4].

Geochemistry and crustal provenance

AGSO and GSWA have compiled a comprehensive whole-rock geochemical database. One of the exciting findings from this has been the recognition of high-Mg diorite (sanukitoid) in the Central Pilbara Tectonic Zone.[9] These rocks, previously only described from Canada, indicate a mantle source that had been modified by subduction. They provide evidence for a setting where, at least in the Central Pilbara Tectonic Zone, the entire thickness of the crust was available for fluid movement at around 2950 Ma. This has implications for fluid movement and tapping into deep crustal and mantle sources at this time. The association of gold at the Towerana porphyry, and an intrusion of the mineralised Mallina Shear Zone, may indicate a link between mineralisation and high-Mg diorite. The recognition of voluminous 2950 million-year-old and younger magmatism along the margin of the Central Pilbara Tectonic Zone and east Pilbara granite–greenstone terrane, in the Yule, Carlindi and Pippingarra granitoid complexes and within the Mallina basin,[9,10] provide further strong evidence for a major thermal event at this time and a favourable environment for mineralisation.

AGSO's contribution to the geochronological database was in dating crustal provenance and inheritance using the Sm-Nd isotopic technique. Nd model ages, when combined with U-Pb zircon ages, provide estimates of crustal residence times. When the ages from the two methods are close (<100 Ma), these data can indicate a juvenile or mantle derivation. If the Sm-Nd age is much older (>100 Ma), it suggests some degree of crustal recycling. A major finding of this work has been the recognition of relatively juvenile crust in the Central Pilbara Tectonic Zone, sandwiched between older crust on the west and east.[11] In the Central Pilbara, Nd isotope model ages of granitic rocks and felsic and mafic volcanic rocks are only 30–130 million years older than their U-Pb emplacement/depositional age. This is consistent with the high-Mg diorite occurrences, all of which suggest that the Central Pilbara Tectonic Zone 'saw' the mantle at various times through its evolution.

Regional synthesis and GIS

Most stakeholders require regional synthesis datasets in order to provide an overarching framework to their targeted areas. AGSO created a comprehensive set of digital themes for the entire Pilbara Craton. Data collection began with acquiring new 400-metre flight-line spaced geophysics (released as map sheet images and digital data), and compiling these surveys into a craton-wide data set. The complete set of geophysical and geological data were released as a two-CD GIS set,[12] a 1:1.5 million scale colour atlas,[13] and a thematic series of 1:500 000 scale maps and images—print-on-demand or postscript files). A 'teaching' GIS of the Marble Bar area was also produced.[14]

The project documented the variety of mineral deposits—especially gold[15], VHMS[4–6,8] Sn-Ta[16]—and high-level deposits[2], and produced databases (GIS) and maps. Results of Pilbara gold are presented as an online record that draws on a guide written for an industry field excursion (June–July 1999) examining the key deposits and relationships.[15] Historical records and information were also captured as part of the synthesis, including the 1930s Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA) reports that are now on CD.[17] They contain much valuable information about deposit location, mine plans, assays, geology and geological maps.

A regional structural synthesis involving a new deformation chronology and kinematics of some of the major shear zones has been documented. These results are presented in a novel CD,[18] with hotlinked images and field photos, which can be read either in a spatial or temporal sense, or in a traditional way. Advances in knowledge of the structural geology include:

1. a better understanding of shear zone timing and movement senses;
2. an improved understanding of the complexity of the polyphase deformation; and
3. recognition of the importance of horizontal compression as a tectonic driving force.

These results provide a clearer link between regional tectonics and mineral deposits, especially in the understanding of the lode gold deposits.

3D geometry of the Pilbara

To understand a mineral system, the three-dimensional architecture of a province needs to be constrained. AGSO developed the first 3D model of the entire North Pilbara region.[7,19] This was achieved by integrating the regional synthesis datasets such as gravity, aeromagnetics and seismic refraction data. Applications of the 3D knowledge include constraints on tectonic models, identification of the important shear zones that transect the crust, and estimates of depth and volumes of metal reservoirs and fluid pathways. Analysis of the geophysical data and 3D model has resulted in the following new observations:

- the Pilbara Craton is ovoid, has a 600 by 550 kilometre diameter, and is only 25 per cent exposed;
- the average crustal depth is 30–32 kilometres (thickening to the south), with the mid-crust at 14 kilometres;
- the greenstones are highly magnetic. Best-fit geophysical modelling shows that the greenstones extend to the base of the mid-crust (14 km), and that most granitoids have steep (vertical) contacts also to the base of the mid-crust (14 km);
- the north-east has on average a more dense and less magnetic crust than the north-west;
- major shear zones are present in the north-west and the far east (Proterozoic reworking); and
- circular patterns of granitoids are everywhere except for the north-west.

Conclusions

The North Pilbara project has made significant advances towards an understanding of the geology and metallogeny, and these results will assist exploration in the Pilbara and other terranes. The geology and metallogeny of the Pilbara Craton, however, differ significantly from the late Archaean provinces such as the Eastern Goldfields and the Superior provinces, so exploration models from these provinces need to be modified for use in the Pilbara Craton. Exploration difficulties will be made easier by the project's work, which includes improved knowledge on the timing and controls of some of the significant mineral systems, new exploration tools and digital datasets, and a new appreciation of the three-dimensional geometry of the granite–greenstone belts.

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