RECORD 1999/6

GOVERNMENT OF WESTERN AUSTRALIA

GSWA 99 EXTENDED ABSTRACTS
New geological data for WA explorers

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 1999/6

GSWA 99 EXTENDED ABSTRACTS
New geological data for WA explorers

30 March 1999

Perth 1999

REFERENCE
The recommended reference for this publication is:

(a) For reference to an individual contribution
VAN KRANENDONK, M. J., 1999, Two-stage degassing of the Archaean mantle: evidence from the 3.46 Ga Panorama volcano, Pilbara Craton, Western Australia, *in* GSWA 99 extended abstracts: New geological data for WA explorers: Western Australia Geological Survey, Record 1999/6, p. 1–3.

(b) For general reference to the publication
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1999, GSWA 99 extended abstracts: New geological data for WA explorers: Western Australia Geological Survey, Record 1999/6, 25p.

National Library of Australia Card Number and ISBN 0 7309 6642 9

Printed by Presspower Pty Ltd

Copies available from:

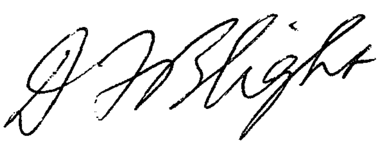
Information Centre
Department of Minerals and Energy
100 Plain Street
EAST PERTH, WESTERN AUSTRALIA 6004
Telephone: (08) 9222 3459 Facsimile: (08) 9222 3444
www.dme.wa.gov.au

Foreword

GSWA 99 marks the second year in which customers of the Geological Survey of Western Australia (GSWA) are invited to listen to talks and to view displays. It follows a successful GSWA 98. The emphasis of the 'open day' is on presenting work-in-progress for our customers and in particular, the mineral industry. The collection of expanded abstracts gathered in this Record relate to the talks and represent a cross section of current GSWA activities.

GSWA 'open days' provide an opportunity for customers to attend a variety of talks by Geological Survey staff on the latest results of their work and to make good use of extended mid-session breaks and lunch time to view the extensive displays. These displays consist of new products and work-in-progress maps, posters, and live PC-based map database demonstrations. Staff are available to field questions and discuss issues related to the displays and other aspects of ongoing GSWA work.

GSWA 'open days' are an opportunity to view the latest data and interpretations pertaining to Western Australia's regional geology and prospectivity. The pre-competitive geological information presented in GSWA 99 provides an example of the way the State assists mineral and petroleum explorers during a time of industry downturn and low commodity prices.



DAVID BLIGHT
DIRECTOR

Contents

Two-stage degassing of the Archaean mantle: evidence from the 3.46 Ga Panorama volcano, Pilbara Craton, Western Australia

by

M. J. Van Kranendonk

The NORTH SHAW 1:100 000 sheet area of the Pilbara Craton is famous for hosting the world's oldest stromatolites in (silicified) carbonate- and sulfate-bearing horizons interbedded with volcanic rocks of the c.3.46 Ga Warrawoona Group. Previously, the origin of carbonate–sulfate deposits has been interpreted as due to evaporative precipitation from shallow seawater (Lambert et al., 1978; Buick and Dunlop, 1990). However, a conformable relationship of these beds on felsic volcanic rocks in one setting, their association with growth faults in another, and the presence of magmatic carbonate in the vent of the 3.46 Ga Panorama felsic volcano, combine to indicate a genetic relationship between volcanism, carbonate–sulfate deposition, and early life (Glasby, 1998).

The best place to observe these relationships is in the North Pole Dome (Fig. 1), where three distinctive carbonate–sulfate units were deposited between c. 3.49 and 3.46 Ga (Richards et al., 1981; Thorpe et al., 1992). The lowest unit is the Towers Formation, which comprises up to three beds of chert–barite–gypsum within a graben underlain by growth faults. Growth faults were filled by chert–barite dykes that form a radial boxwork set emanating from the core of the dome. In the bedded sequence, gypsum and barite occur both in bedded deposits and as diagenetic minerals. The occurrence of barite mounds over terminations of the growth faults (Nijman et al., 1998), of barite in the growth fault dykes, and of bedded barite and gypsum (Buick and Dunlop, 1990; Nijman et al., 1998), combine to indicate an exhalative origin for some of the sulfates. A previous suggestion that barite–chert dykes were formed by later doming (Buick and Dunlop, 1990) is unlikely because the dykes are restricted to below the Towers Formation, and because thickness variations of bedded deposits relate to the growth faults. An exhalative origin for sulfates is confirmed by identical magmatic $\delta^{34}S$ values of +3.6 ± 0.5‰ for both bedded and discordant barite (Lambert et al., 1978).

The second unit, which is barren of stromatolites, consists of lower and upper felsic tuff beds, bounding an 8 m-thick sequence of cross-bedded to massive carbonate-altered tuff. Petrographic textures indicate that the carbonate is largely of replacement origin, but this is difficult to reconcile with the observation that the carbonate horizon is bound above and below by unaltered felsic volcaniclastic rocks.

The overlying Strelley Pool Chert, which contains abundant and widespread stromatolites, occurs on felsic volcaniclastic rocks of the 3.46 Ga Panorama Formation. The Strelley Pool Chert is up to 20 m thick, and consists of thinly bedded carbonate, beds with gypsum-crystal rosettes, and wavy-laminated rocks interpreted to have

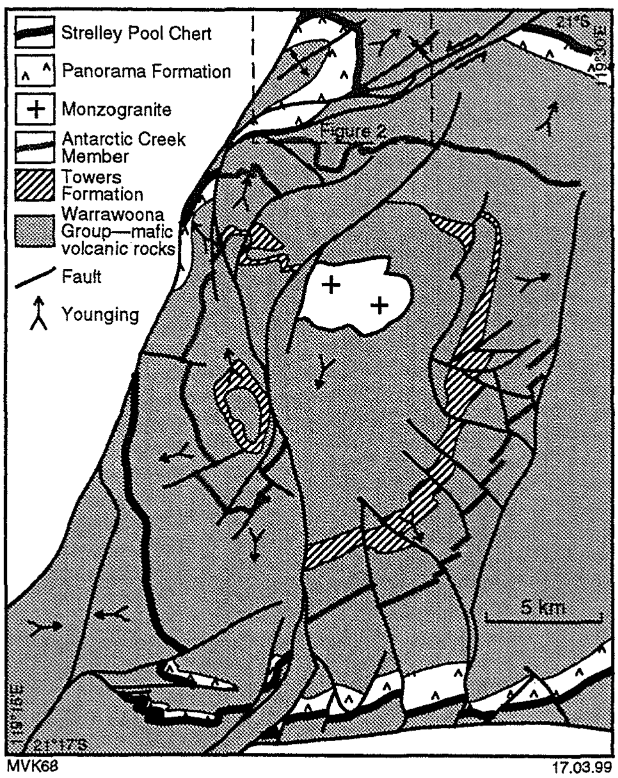


Figure 1. Carbonate/sulfate-bearing horizons of the North Pole Dome

formed by the transformation of anhydrite to gypsum. In some places, the wavy-laminated rocks and beds with gypsum or aragonite crystal splays have been replaced by diagenetic carbonate (ferroan dolomite and/or ankerite), indicating both a depositional and a replacement origin for the carbonates. The presence of evaporitic solution breccias at specific stratigraphic levels indicates periodic supratidal exposure, whereas evidence of wave action at other stratigraphic levels suggests periodic shallow-marine conditions (Buick and Dunlop, 1990).

The key to the origin of carbonate–sulfate assemblages and their relationship to felsic volcanism lies in the Panorama felsic volcano, which has been tilted by late folding to provide a cross-sectional view (Fig. 2). The volcano comprises a vent of unsorted breccia that is rimmed by, and cuts through, an apron of jaspilitic banded iron-formation. Adjacent to the vent is a kilometre-thick volcaniclastic apron, over which the Strelley Pool Chert is absent. The volcaniclastic rocks comprise, from base to top, bedded carbonate and jasper, volcaniclastic debris flows with abundant jasper fragments, finer grained volcaniclastic rocks with local pumiceous beds, and cross-bedded volcaniclastic siltstones. Proximal to the vent, volcaniclastic rocks contain abundant carbonate (ferroan dolomite ± ankerite) in the matrix, and are locally cut by metre-wide carbonate dykes. Distal to the vent, an almost identical sequence lacks carbonate. Within the vent, the unsorted felsic volcanic breccia is cut in three places by small, dark-brown carbonate plugs, the smallest of which is 1m in diameter and packed with angular jasper fragments, texturally identical to flanking debris flows.

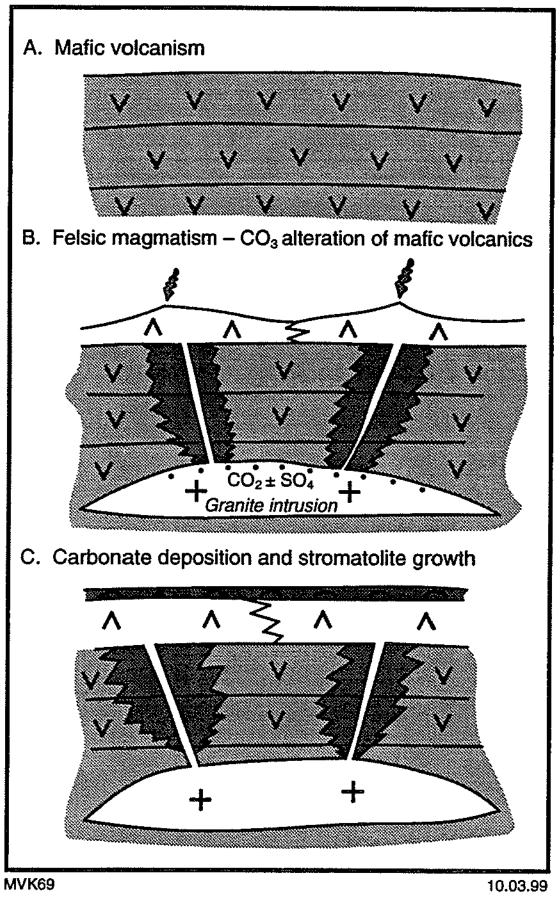


Figure 3. Model for carbonate/sulfate deposition during felsic volcanism

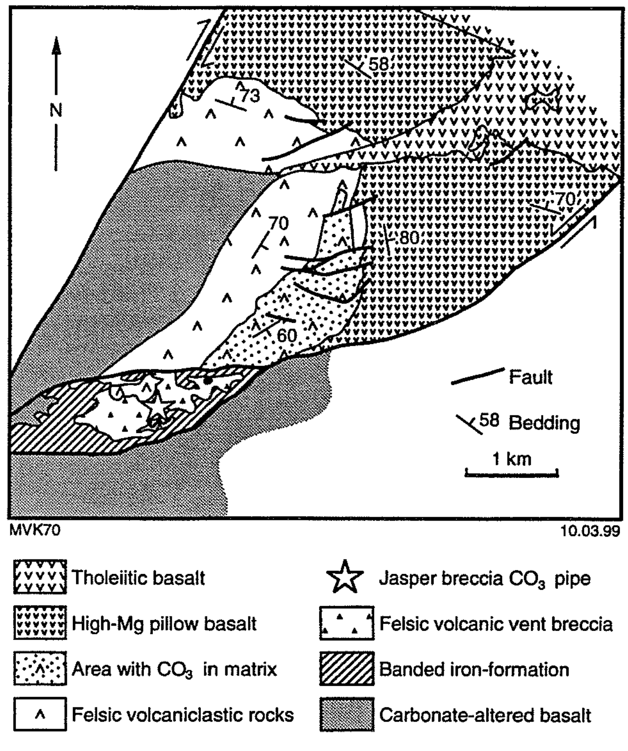


Figure 2. Geology of the Panorama volcano

Petrography of the breccia pipe shows that carbonate is restricted to the matrix and absent from included fragments of dacite and jasper. In the matrix, silica occurs both as a fine-grained component with rhomboid carbonate, and also as irregularly shaped, texturally-zoned, monomineralic patches between carbonate-bearing areas. The outer zone of silica in these patches forms radially fibrous crystals that nucleated on the terminations of carbonate rhombs. In the bigger patches, the fibrous zone grades into an inner zone of equigranular, granoblastic quartz. These textures are indicative of boiling fluids and of immiscibility between consanguineous carbonate-bearing and carbonate-absent fluids. It is thus clear that carbonate was an integral part of the matrix during magmatism, and not an introduced component during alteration. Additional evidence of a magmatic origin for carbonate is indicated by the fact that felsic feeder dykes to the Panorama Formation have a wide carbonate halo in host mafic volcanic rocks. Indeed, this carbonate alteration extends throughout the underlying pillowed mafic volcanic rocks, in sharp contrast to overlying mafic volcanic rocks that are far less altered.

This evidence suggests that Archaean carbonate is not derived solely through precipitation from seawater. Instead, it is proposed that the $CO_2 \pm SO_4$ in Early

Archaean Pilbara deposits was largely sourced from oxidized volcanic exhalations, and that these exhalations produced locally oxygenic conditions suitable for habitation by early microbial organisms. Whereas precipitation of carbonate–sulfate from seawater must have played a part in the formation of these units, it is argued that such unusually oxygenating conditions (i.e. Archaean seawater typically precipitated silica and had a lower partial pressure of sulfate than the present day; De Ronde et al., 1998) were locally developed in response to volcanic exhalations. A crustal melt origin for the Panorama Formation (Cullers et al., 1993) indicates that the carbonate–sulfate, and the iron around the vent of the Panorama volcano, were probably scavenged from older mafic volcanic rocks during melting and magma genesis. In this sense, carbonate–sulfate deposition in Archaean units reflects two-stage degassing of the Archaean mantle (Fig. 3).

References

BUICK, R., and DUNLOP, J., 1990, Evaporitic sediments of early Archaean age from the Warrawoona Group, North Pole, Western Australia: Sedimentology, v. 37, p. 247–277.

CULLERS, R., DiMARCO, M., LOWE, D., and STONE, J., 1993, Geochemistry of a silicified, felsic volcaniclastic suite from the early Archaean Panorama Formation, Pilbara Block, Western Australia: an evaluation of depositional and post-depositional processes with special emphasis on the rare-earth elements: Precambrian Research, v. 60, p. 99–116.

DE RONDE, C., CHANNER, D., and SPOONER, E., 1998, Archean Fluids, *in* Greenstone Belts *edited by* M. DE WIT and L. ASHWAL: Oxford Monographs on Geology and Geophysics, no. 35, p. 309–335.

GLASBY, G. P., 1998, Earliest life in the Archean: Rapid dispersal of CO_2-utilizing bacteria from submarine hydrothermal vents: Episodes, v. 21, p. 252–256.

LAMBERT, I., DONNELLY, T., DUNLOP, J., and GROVES, D., 1978, Stable isotopic compositions of early Archaean sulfate deposits of probable evaporitic and volcanogenic origins: Nature, v. 276, p. 808–811.

NIJMAN, W., DE BRUIN, K., and VALKERING, M., 1998, Growth fault control of early Archaean cherts, barite mounds, and chert-barite veins, North Pole Dome, Eastern Pilbara, Western Australia: Precambrian Research, v. 88, p. 25–52.

RICHARDS, J., FLETCHER, I., and BLOCKLEY, J., 1981, Pilbara galenas: precise isotopic assay of the oldest Australian leads; model ages and growth-curve implications: Mineralia Deposita, v. 16, p. 7–30.

THORPE, R., HICKMAN, A., DAVIS, D., MORTENSEN, J., and TRENDALL, A. F., 1992, U-Pb zircon geochronology of Archaean felsic units in the Marble Bar region, Pilbara Craton, Western Australia: Precambrian Research, v. 56, p. 169–189.

New tectono-stratigraphic interpretations of the Pilbara Craton, Western Australia

by

A. H. Hickman

The Geological Survey of Western Australia (GSWA) program of 1:100 000-scale geological mapping in the north Pilbara granite–greenstone terrane has now been in progress for four years, and the new information obtained has led to major reinterpretations of the region's stratigraphy, structure and tectonic evolution. The mapping forms part of a joint project between GSWA and the Australian Geological Survey Organisation (AGSO), and currently employs about ten geoscientists. Most of the geological field mapping is being undertaken by GSWA, whereas AGSO staff are concentrating on mineralization and the interpretation of regional airborne magnetic, gamma-ray spectrometric, and gravity data.

Previous geological interpretations of the Pilbara Craton are generalized into two distinct models:

1. In the regional interpretation presented by Hickman (1983), the north Pilbara granite–greenstone terrane evolved from a single segment of continental crust formed at about 3500 Ma. The greenstone belts are the synformal remnants of a craton-wide 3500–2900 Ma supracrustal succession of volcanic and sedimentary rocks, referred to as the Pilbara Supergroup. Lower parts of this succession exhibit an essentially 'layer-cake' stratigraphy, with the same formations occurring in most greenstone belts of the east and west Pilbara. Upper units of the Pilbara Supergroup were deposited after diapiric deformation, and were restricted to separate basins. A lithostratigraphic subdivision was applied to the greenstone succession.
2. In the late 1980s and 1990s various workers interpreted the north Pilbara granite–greenstone terrane as an assemblage of tectono-stratigraphic domains. These domains are separated by northeast–southwesterly trending faults considered to have a long history of development and reactivation (Krapez, 1993). Using principles of sequence stratigraphy the greenstones are subdivided into four megasequences, each representing a megacycle of fore-arc, arc, and/or back-arc geotectonic evolution associated with convergent margin processes. Seventeen second-order supersequences record separate basins or basin phases. According to Barley (1997) the supersequences are stacked, recording progressive westwards growth (accretion?) of the craton, and can be related to the opening and closure of ocean basins.

The 1:100 000 mapping between 1995 and 1999 has established that the north Pilbara granite–greenstone terrane can be divided into western and eastern terranes separated by the Mallina Basin (Fig. 1). These two terranes exhibit different tectonic styles and major stratigraphic differences.

The western terrane, which comprises the Whim Creek Belt and all units to the west of this, is characterized by northeast-trending granitoid complexes and greenstone belts, numerous closely spaced east- and northeast-striking faults, and by granitoids which are structurally relatively simple and discordant to the greenstone stratigraphy. In contrast, the eastern terrane is dominated by dome-and-syncline structures in which the granitoid complexes are composite ovoid structures, and the greenstone belts exhibit no preferred structural trend. Granite–greenstone contacts are generally sheared, and parallel to adjacent greenstone stratigraphy.

Stratigraphic differences between the two terranes are very considerable, although the precise degree of difference is still being tested. In particular, the oldest rocks of the western terrane are 3270 Ma, and the 3490–3420 Ma Warrawoona Group is absent. In the eastern terrane the oldest rocks are 3660–3590 Ma gneisses (Nelson, in prep.), and the oldest greenstones are 3515 Ma. In addition, the east Pilbara contains no equivalents of the 3125–3115 Ma Whundo Group or the 3010–3000 Ma Whim Creek Group.

The differences between the western and eastern terranes are not explained by progressive westward accretion. Geochronology from the eastern terrane has identified rocks older than 3400 Ma near its eastern and western margins, indicating no trend of east-west younging. Moreover, the western terrane has provided isotopic evidence for 3490–3450 Ma sources for certain of its granitoids and greenstones. Both terranes contain stratigraphic units and granitoids spanning the 3270–

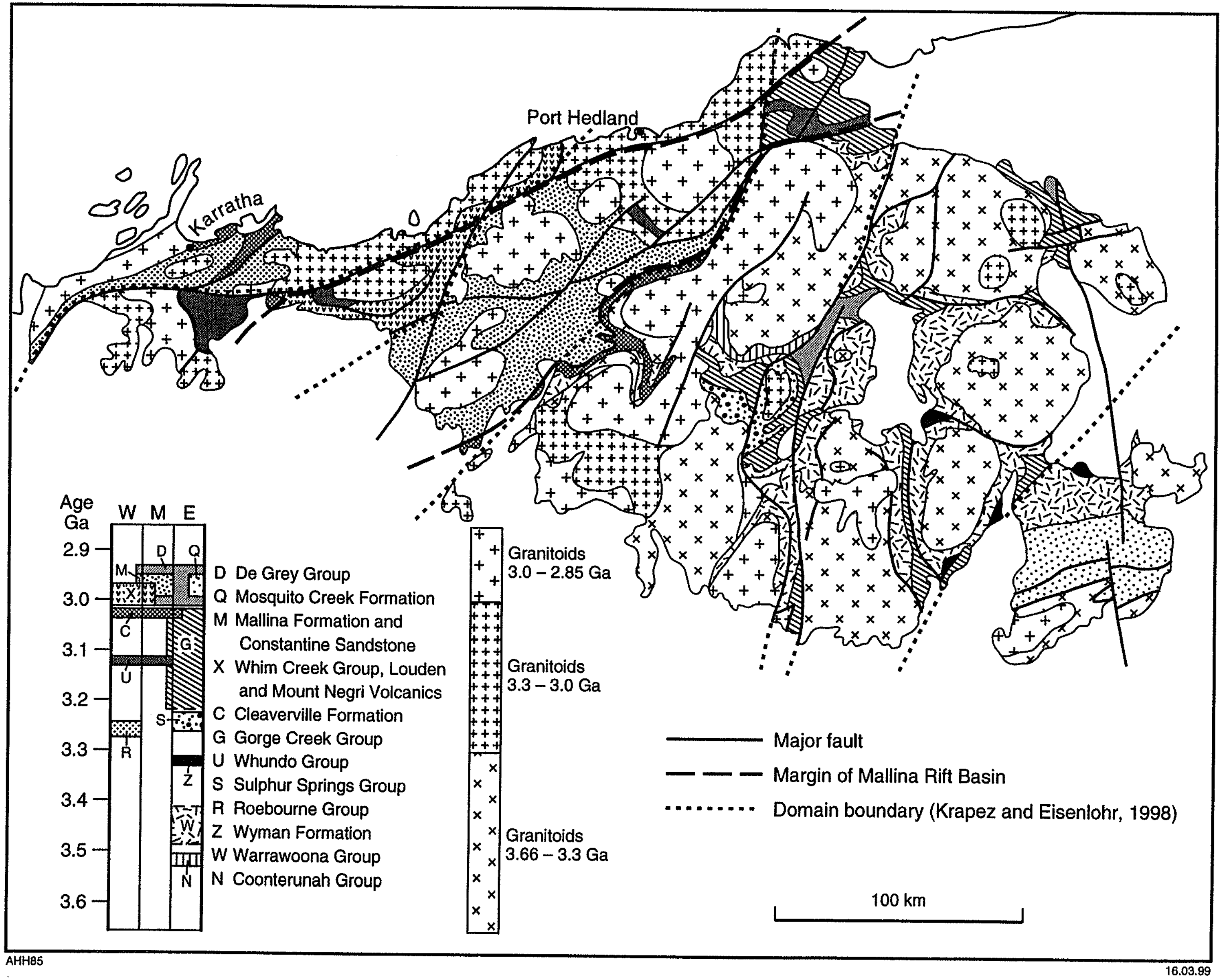


Figure 1. Tectono-stratigraphy of the north Pilbara granite–greenstone terranes

2920 Ma age range, and stratigraphic correlation may eventually be confirmed between 3270–3250 Ma formations of the Roebourne Group and the c. 3260–3240 Ma Sulphur Springs Group. The two terranes were in contact before 3020 Ma because the 3020–3015 Ma Cleaverville Formation occurs in both. Certainly, convergent-margin environments can explain some of the west Pilbara units, probably from 3130 Ma onwards, and this is consistent with their location on the northwestern margin of the Pilbara Craton.

The five northeast-trending domain boundaries, claimed by Krapez and Eisenlohr (1998) to be long-lived crustal structures, appear to be merely late-stage (c. 3050–2900 Ma) strike-slip faults. No major structural or stratigraphic differences have been established across the two lineaments in the eastern terrane; mapping of the eastern margin of the Mallina Basin has shown that the lineament proposed here is not a continuous structure; and the lineament near the western margin of the Mallina Basin, crosses the Mallina Basin–Whim Creek Group association. The Sholl Shear Zone (the most westerly lineament) records post-3010 Ma (probably also post-2925 Ma) dextral movement of 30–40 km, displacing the Whim Creek Group, the Cleaverville Formation, and the Andover Intrusion (Hickman, in prep.). Greater, sinistral movement occurred at some time between 3115 Ma (Whundo Group) and 3015 Ma. Shear zones within the Mallina Basin may represent post-3000 Ma reactivation of a concealed tectonic zone separating the eastern and western terranes.

Mapping of the western terrane, and the greater part of the Mallina Basin, is now complete, and has resulted in a major revision of the stratigraphic succession. Restricted to the area south of the Sholl Shear Zone, the volcanic rocks of the 3125–3115 Ma Whundo Group were derived from juvenile crust, possibly in a subduction-zone environment (Smith et al., 1998; Sun and Hickman, 1998). In contrast, the 3270–3250 Ma Roebourne Group occurs only north of the Sholl Shear Zone, and Nd-isotopic data indicate derivation from much older rocks (Sun and Hickman, 1998). The Cleaverville Formation has been dated at 3020–3015 Ma, overlies both the Whundo Group and the Roebourne Group and, in addition, provides a stratigraphic link between the western and eastern terranes. The 3010 Ma Whim Creek Group unconformably overlies the Whundo Group and the Cleaverville Formation, and at least partly underlies the Mallina Formation. The Mallina Basin post-dates 3000 Ma, and is an extensional basin underlain by continental crust (Smithies et al., 1999).

New information from the east Pilbara includes identification of 3660–3590 Ma gneiss, separation of the 3260–3240 Ma Sulphur Springs Group from the much older Warrawoona Group, and detailed subdivisions of the Gorge Creek Group in two areas. Additionally, mapping and geochronology around Marble Bar have clearly demonstrated that the Warrawoona Group is not tectonically duplicated or inverted by major horizontal movements, as was proposed by Van Haaften and White (1998), but is a normal, 13 km-thick succession, as originally interpreted by Hickman (1983). Another important development has been confirmation of the diapiric model for dome and sycline development (Van Kranendonk and Collins, in press).

References

BARLEY, M. E., 1997, The Pilbara Craton, *in* Greenstone belts *edited by* M. J. DE WIT and L. D. ASHWAL: Oxford Monographs on Geology and Geophysics, Number 35, p. 657–664.

HICKMAN, A. H., 1983, Geology of the Pilbara Block and its environs: Western Australia Geological Survey, Bulletin 127, 268p.

HICKMAN, A. H., in prep., Dampier, W.A. Sheet 2256: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

KRAPEZ, B., 1993, Sequence stratigraphy of the Archaean supracrustal belts of the Pilbara Block, Western Australia: Precambrian Research, v. 60, p. 1–45.

KRAPEZ, B., and EISENLOHR, B., 1998, Tectonic settings of Archaean (3325–2775 Ma) crustal–supracrustal belts in the West Pilbara Block: Precambrian Research, v. 88, p. 173–205.

NELSON, D. R., in prep., Compilation of SHRIMP U–Pb zircon geochronology data, 1998. Western Australia Geological Survey, Record 1999/2.

SMITH, J. B., BARLEY, M. E., GROVES, D. I., KRAPEZ, B., McNAUGHTON, N. J., BICKLE, M. J., and CHAPMAN, H. J., 1998, The Sholl Shear Zone, West Pilbara: evidence for a domain boundary structure from integrated tectonic analyses, SHRIMP U-Pb dating and isotopic and geochemical data of granitoids: Precambrian Research, v. 88, p 143–171.

SMITHIES, R. H., HICKMAN, A. H. and NELSON, D. R., 1999, Reassessment of the evolution of the Whim Creek Group, western Pilbara Craton, in the light of new geological and geochronological data: Precambrian Research, v. 94, p. 11–28.

SUN, S-S., and HICKMAN, A. H., 1998, New Nd-isotopic and geochemical data from the west Pilbara: implications for Archaean crustal accretion and shear zone movement: Australian Geological Research Newsletter, May 1998, p. 25–29.

VAN HAAFTEN, W. M., and WHITE, S. H., 1998, Evidence for multiphase deformation in the Archean basal Warrawoona Group in the Marble Bar area, East Pilbara, Western Australia: Precambrian Research, v. 88, p. 53–66.

VAN KRANENDONK, M. J., and COLLINS, W. J., in press, Partial convective overturn of the eastern part of the Archaean Pilbara Craton, Western Australia: Field evidence for the diapiric emplacement of granitoid domes: Earth Science Reviews.

West Pilbara mineralization mapping, Western Australia

by

I. Ruddock

The west Pilbara project includes the area of four 1:250 000 sheets: DAMPIER, ROEBOURNE, PYRAMID, and YARRALOOLA. The area is one of the cornerstones of the State's economy and future prosperity, with major contributions from the North West Shelf Gas Project at Burrup Peninsula, the Robe River iron ore mines, and the iron ore export facilities at Dampier and Cape Lambert. The purpose of the west Pilbara project is to promote the area's mineral exploration potential by providing industry with a data package comprising a report, a map, and digital spatial indexes for exploration activities and all known mineral occurences.

Geologically, the west Pilbara includes the Pilbara Craton, except in the southwest where it includes the northern edges of the Ashburton Basin and the onshore Carnarvon Basin. The region contains a broad range of mineral commodities which include iron ore, nickel, base metals, gold, silver, platinum-group elements, titanium, vanadium, antimony, tin, and beryl. There is a long mining history going back to the 1870s, and the gold discovery at Mallina Homestead in 1888 sparked a gold rush that spread through the whole Pilbara. Copper mining at Whim Creek also started at about that time, and during the 1890s there were numerous other discoveries of gold and copper which were developed as small mines.

Mining activity waned in the early part of the 20th century, but this changed dramatically in the west Pilbara when the iron ore export embargo was lifted in the early 1960s, and there was a surge in iron ore exploration in the Robe River area where large resources of pisolitic iron were delineated. During the 'nickel boom' of the late 1960s and early 1970s, the area from Dampier to Whim Creek was a major focus for nickel–copper and copper–zinc exploration and several discoveries were made. Nickel deposits were located at Mount Sholl, Ruth Well, Radio Hill, and Sherlock Bay; copper–zinc resources were outlined at the old mining areas of Whundo and Mons Cupri (the base metal deposit at Salt Creek was discovered later, in 1977). Vanadium–titanium deposits were also outlined in the mid- to late 1960s at Ball Balla and Don Well. In the mid-1980s the west Pilbara became a focus for platinum-group element exploration in layered mafic intrusions, and a deposit was discovered at Munni Munni. In 1987 a small but very rich silver deposit was also found at Elizabeth Hill, just north of Munni Munni.

Although mineral exploration in the area has fallen behind some other parts of the State since the late 1980s, there has been a recent revival in nickel exploration in layered intrusions of the west Pilbara following the discovery of the huge Voisey's Bay deposit in Labrador (in 1994) and a revival of regional gold exploration for turbidite-hosted vein-gold deposits following new discoveries in the Mallina Basin in 1997.

New mine developments include the reopening of the Radio Hill nickel mine in April 1998 and plans to open a new silver mine at Elizabeth Hill. In addition, there are plans to restart copper mining at Whim Creek and Mons Cupri, and in late 1998 it was announced that the vanadium deposits at Balla Balla may be developed using new metallurgical techniques.

Four hundred and thirty-five mineral occurrences have been identified in the present study and most of them are in the greenstone sequences and layered mafic intrusions of the Archaean North Pilbara granite–greenstone terrane; in the south, most of the occurrences are pisolitic iron ore deposits in Cainozoic palaeochannels in the Robe and Fortescue valleys. The mineral occurrences have been categorized into seven styles of mineralization:

Orthomagmatic mafic and ultramafic

Stratiform sedimentary and volcanic

Vein and hydrothermal

Stratabound (clastic hosted)

Disseminated and stockwork in felsic plutons

Pegmatitic

Sedimentary — alluvial

The main styles targeted for exploration in the area (apart from iron ore) have been the first three listed above.

Orthomagmatic mineralization occurrences are in the layered mafic–ultramafic intrusions, where the main commodities are:

Nickel–copper (Radio Hill, Sholl, Sherlock)

Vanadium–titanium (Sherlock and Andover)

Platinum-group elements (Munni Munni and Radio Hill)

Chromium (Munni Munni and Sherlock)

A few nickel occurrences are also developed in komatiite–high-Mg basalt sequences (Ruth Well).

Stratiform sedimentary and volcanic (volcanic massive sulfide) occurrences of copper–zinc (lead and silver) are located in two main areas of greenstones: the Whim Creek belt in the east and the Sholl belt in the west. Another area with volcanic massive sulfide (VMS) potential is at Shepherd Well in the far west. More recently, VMS potential has been highlighted in the Hamersley Basin, in felsic volcanic units of the Fortescue Group, as a result of GSWA mapping on the PINDERI HILLS 1:100 000 sheet.

Nearly all vein and hydrothermal gold occurs in the granite–greenstone sequences. The most significant occurrences are hosted by metasedimentary rocks in the east in the Mallina Basin. These are known as 'turbidite-hosted gold' occurrences, similar to the Ballarat–Bendigo area in Victoria, the Hodgkinson Basin in northeast Queensland, and several other major gold producing areas around the world. The main structural controls on mineralization in the Mallina Basin are the east-northeasterly trending Mallina Shear and Sholl Shear, and splays from these.

In the west, vein gold is hosted by mafic and ultramafic volcanic rocks, and the main structural control on mineralization is the east-northeasterly trending Sholl Shear and splays from this.

The west Pilbara project also includes the completion of a spatial index for all mineral-exploration activities contained in WAMEX reports that are available to the public on open file. Exploration intensity in prospective zones can be demonstrated using a selection of themes; for example, the distribution of geochemical grid surveys, ground EM and IP surveys, and drilling. For the west Pilbara, the distribution of these three types of exploration activities shows that there are gaps in the data over many areas. The reason for these gaps is due to two factors:

a) the areas were not considered worthy of further investigation beyond initial regional geochemical surveys and airborne geophysical surveys (most likely due to the limitations of older surveys), or

b) the data are actually in WAMEX reports but these are not yet on open file.

The west Pilbara must still be considered as one of the most prospective underexplored parts of the State for a large range of commodities in a variety of mineralization styles. Many areas have been highlighted during past exploration as being prospective for base metal sulfides, nickel–copper sulfides, platinum-group elements, and gold, but they have yet to be fully tested by the latest geochemical and geophysical methods used in industry, and be assessed in the light of new geological concepts arising from the Survey's current 1:100 000-scale mapping program and the airborne geophysical surveys undertaken by AGSO as part of the National Geoscience Mapping Accord.

The Palaeoproterozoic tectonic evolution of the southern margin of the Capricorn Orogen, Western Australia

by

I. M. Tyler, S. A. Occhipinti and S. Sheppard

The Capricorn Orogen is a major Proterozoic tectonic zone that developed between the Archaean Yilgarn and Pilbara Cratons. New 1:100 000-scale geological maps have been produced from the southern part of the Orogen (MARQUIS — Sheppard et al., in press a; MOORARIE — Occhipinti and Myers, in press; ERRABIDDY — Occhipinti and Sheppard, 1999; LANDOR — Sheppard and Occhipinti, in press), with several others in the process of being compiled (GOULD, GLENBURGH, and ERONG). This detailed mapping, combined with geochemical data (Sheppard et al., in press b) and new geochronological results (Nelson, 1998, in prep.), has defined two major Palaeoproterozoic tectonic events: one at 2000 to 1975 Ma and a second at 1830 to 1780 Ma.

The southern part of the Capricorn Orogen (Fig.1) includes the Palaeoproterozoic volcano-sedimentary Bryah and Padbury Basins, medium- to high-grade latest Archaean to Palaeoproterozoic meta-igneous and metasedimentary rocks of the Gascoyne Complex, and the Yarlarweelor gneiss complex, which consists of reworked Archaean crust of the Yilgarn Craton. The boundary between the Yilgarn Craton and the Gascoyne Complex is marked by the Errabiddy Shear Zone.

Tonalites and monzogranites were intruded into the southern Gascoyne Complex at c. 2000 Ma. There is evidence of latest Archaean to earliest Palaeoproterozoic crust with an age of c. 2500 Ma reported by Nutman and Kinny (1994) from granitic gneiss in the Carrandibby Inlier. Calc-silicate and pelitic schists and gneisses of the Camel Hills Metamorphics outcrop between the Gascoyne Complex and the Yilgarn Craton, and were deposited at c. 2000 Ma. The calc-silicate rocks contain Archaean detrital zircons that were apparently derived from the Yilgarn Craton. However in the pelitic rocks, early Palaeoproterozoic zircons dominate the detrital population and must have had a different source region.

The c. 2000 Ma tonalites and monzogranites were heterogeneously deformed before being intruded by voluminous granodiorite and monzogranite at c. 1975 Ma. The 2000 to 1975 Ma granitic rocks do not intrude the Archaean Yilgarn Craton and are interpreted as a separate Palaeoproterozoic terrane which may represent a convergent continental margin that developed above a northwesterly dipping subduction zone. Magmatism accompanied high-grade metamorphism, with the local migmatization of pelitic rocks taking place at the same time as the formation of a layer-parallel tectonic fabric. Deformation and metamorphism may reflect collision of this Palaeoproterozoic terrane and the Yilgarn Craton at c. 1970 Ma. The northern edge of the Yilgarn Craton was intruded by post-collisional monzogranites at c. 1960 Ma. This collisional event is significantly older than the c. 1840 to 1800 Ma Capricorn Orogeny of Tyler et al. (1998) and is named the Glenburgh Orogeny.

The Bryah Basin outcrops to the east of the Gascoyne Complex and records a history of mafic to ultramafic volcanic and intrusive activity followed by the deposition of sedimentary rocks (Pirajno et al., 1998). It may represent a back-arc basin developed during convergence that involved the southward subduction of oceanic crust between the Pilbara and Yilgarn Cratons between c. 1960 and 1830 Ma

The c. 1830 to 1780 Ma event is equated with the final stages of the Capricorn Orogeny, which has been interpreted as reflecting the collision between the Archaean Yilgarn and Pilbara Cratons (Tyler and Thorne, 1990). Extensive felsic magmatism occurred throughout the southern part of the Capricorn Orogen between c. 1830 and 1780 Ma. In the Yarlarweelor gneiss complex Archaean granitic gneiss was intruded at c. 1810 Ma by sheets and veins of leucocratic granite (Occhipinti et al., 1998). Intrusion took place parallel to an Archaean gneissosity that is reorientated by Palaeoproterozoic east- to northeast-trending tight to isoclinal upright folds. Locally, the granites cut the gneissosity but are also seen to be folded with it. The c. 1810 Ma granites were emplaced during upper amphibolite facies metamorphism and locally show incipient partial melting. In contrast, the c. 1800 Ma granites form dykes and large sheet-like bodies intruded into major east-southeasterly trending fault zones that cut the c. 1810 Ma granite. The younger granites contain sericitized feldspar and chlorite (after biotite) indicating a greenschist facies metamorphic overprint.

The change in deformation regime from ductile to brittle, and the coincident drop in metamorphic grade from upper amphibolite to greenschist facies, implies that tectonic uplift took place between 1810 and 1800 Ma in the southern part of the Capricorn Orogen. This involved thrusting of the Yarlarweelor gneiss complex over the Yilgarn Craton, and reactivation of the Errabiddy Shear Zone. The Padbury Basin probably developed as a foreland basin (Martin, 1994). The low-grade meta-sedimentary and meta-igneous rocks of the Bryah and Padbury Basins were tectonically interleaved with the Yarlarweelor gneiss complex during this event. The voluminous biotite and muscovite-bearing monzogranites and syenogranites that intruded into the Yarlarweelor gneiss complex and Gascoyne Complex are consistent with syn- to post-collisional magmatism.

References

MARTIN, D. M., 1994. Sedimentology, sequence stratigraphy, and tectonic setting of a Palaeoproterozoic turbidite complex, Lower Padbury Group, Western Australia: University of Western Australia, Ph.D. thesis (unpublished).

NELSON, D. R., 1998. Compilation of SHRIMP U–Pb zircon geochronology data, 1997: Western Australia Geological Survey, Record 1998/2.

NELSON, D. R., in prep., Compilation of SHRIMP U–Pb zircon geochronology data, 1998. Western Australia Geological Survey, Record 1999/2.

NUTMAN, A. P., and KINNY, P. D., 1994, SHRIMP zircon geochronology of the southern Gascoyne Province and the northwestern margin of the Yilgarn Craton, W.A.: Geological Society of Australia, Abstracts, v. 37, p. 320–321.

OCCHIPINTI, S. A., and MYERS, J. S., in press, Moorarie, W. A. Sheet 2446: Western Australia Geological Survey, 1:100 000 Geological Series.

OCCHIPINTI, S. A., and SHEPPARD, S., 1999, Errabiddy, W. A. Sheet 2347 (Preliminary Edition): Western Australia Geological Survey, 1:100 000 Geological Series.

OCCHIPINTI, S. A., SHEPPARD, S., NELSON, D. R., MYERS, J. S., and TYLER, I. M., 1998, Syntectonic granite in the southern margin of the Palaeoproterozoic Capricorn Orogen, Western Australia: Australian Journal of Earth Sciences, v. 45, p. 509–512.

PIRAJNO, F., OCCHIPINTI, S. A., and SWAGER, C. P., 1998, Geology and tectonic evolution of the Palaeoproterozoic Bryah, Padbury and Yerrida Basins (formerly Glengarry Basin), Western Australia: implications for the history of the south-central Capricorn Orogen: Precambrian Research v. 90, p. 119–140.

SHEPPARD, S., and OCCHIPINTI, S. A., in press, Landor, W. A. Sheet 2247: Western Australia Geological Survey, 1:100 000 Geological Series.

SHEPPARD, S., OCCHIPINTI, S. A., TYLER, I. M., and NELSON, D. R., in press b, The nature of c. 2.0 Ga crust in the southern part of the Gascoyne Complex: Western Australia Geological Survey, Annual Review for 1998-99.

SHEPPARD, S., SWAGER, C. P., MYERS, J. S., and OCCHIPINTI, S. A., in press a, Marquis, W. A. Sheet 2447: Western Australia Geological Survey, 1:100 000 Geological Series.

TYLER, I. M., and THORNE, A. M., 1990, The northern margin of the Capricorn Orogen, Western Australia — an example of an early Proterozoic collision zone: Journal of Structural Geology v. 12, p. 685–701.

TYLER, I. M., PIRAJNO, F., BAGAS, L., MYERS, J. S., and PRESTON, W. A., 1998, The geology and mineral deposits of the Proterozoic in Western Australia: AGSO Journal of Australian Geology and Geophysics, v. 17, p. 223–244.

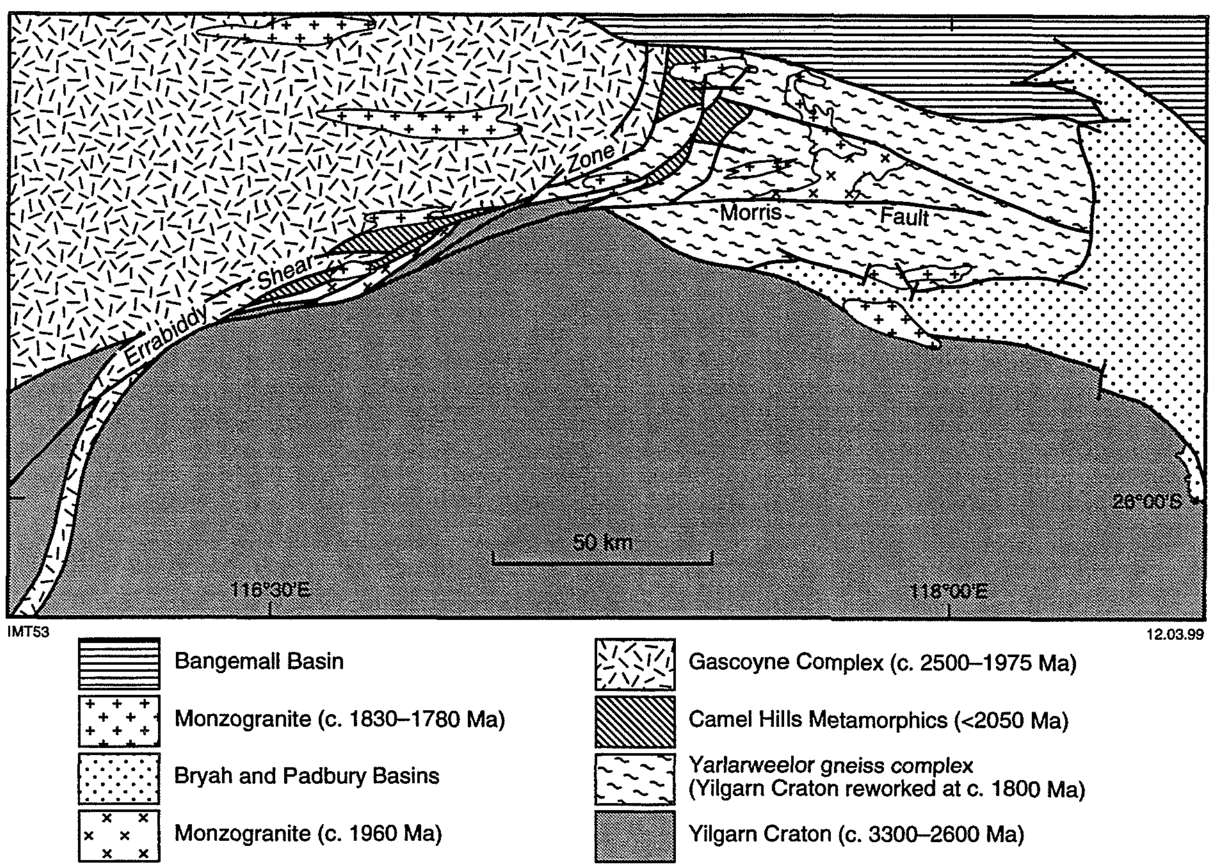


Figure 1. Geology of the northwestern Yilgarn Craton and southern Gascoyne Complex

Submission of digital mineral exploration data — moving toward a national standard

by

J. H. Haworth

In March 1999, the Department of Minerals and Energy began accepting in digital format a wide range of statutory mineral exploration reports, data and information from tenement holders. At this stage, submission of statutory information in digital format is not compulsory.

Submission of reports conforming to the 'Requirements for the Submission of Mineral Exploration Information in Digital Format' will mean that tenement holders 'reach agreement with the Director, Geological Survey of Western Australia in regard to the required format [for digital data]' under Note 8 of the 'Guidelines for Mineral Exploration Reports on Mining Tenements' issued in accordance with Section 115A of the Mining Act 1978.

The 'Requirements' have evolved out of consultation between industry groups and representatives, followed by discussions with authorities in other States responsible for custodianship of statutory mineral exploration reports. A draft of the 'Requirements' was subsequently considered by the Government Geologist's Information Policy Advisory Committee (GGIPAC) and has been accepted with minor amendment as a standard that will be used by most State governments.

The purpose of setting standard formats for digital data is to ensure industry submits complete datasets in a format capable of being read five to ten years in the future.

This paper comprises a subset of standard formats expressly for use in Western Australia. Table 1 contains a summary of the requirements for various types of digital data.

Additional information on data types

Tabular data: for example geochemistry, hole collar locations, lithology logs and downhole survey data, to be submitted as ASCII tab-delimited files complete with metadata as per the 'Requirements', or in the AMIRA P431 or PPDM data model formats.

Geophysical data other than seismic: these data include magnetic, gravity, radiometric, electromagnetic (e.g. TEM, SIROTEM), and for both raw and processed located data the standard ASEG GDF2 format is required. Gridded data must be submitted in either ASEG GXF or ER Mapper gridded format.

Geophysical images: these are images derived from magnetics or gravity and include TMI and Bouguer images. As for maps, these should be submitted as PDF, TIFF, or EPS depending on the size of the full-scale plot.

Seismic data, petrophysical and geophysical log data, and downhole velocity data: international standards already exist for these data (Table 1).

Geo-referenced spatial data (polygons and lines): geo-referenced spatial data include multi-vector polygons or lines that relate to geology, geography or exploration activities (e.g. exploration activity area polygons, sampling traverses, areas drilled, etc). Maps and plans from derived datasets should be submitted in PDF or TIFF formats. The data dictionary should provide a full explanation of information provided in the polygon attribute file where codes are used in the data.

Text: including figures and tables normally provided in hard copy reports, must be submitted as PDF with the security set to allow copy and paste but not to edit the document.

Maps, plans and figures (not forming part of text): should be submitted in either PDF (preferably), TIFF or EPS formats.

Photographs (not forming part of text): these include core photographs, environmental photographs etc. and should be submitted as either PNG or JPG files.

Tabular data

The main issues involved in the submission of digital tabular data concern the variety of data types received and the lack of 'standards' applied to some of these data. In an attempt to minimize the impact of these issues, a system

Table 1. Acceptable formats for digital data submitted as part of statutory mineral exploration reports

Data type	*Description*	*Format*	*Parameter*	*Suffix*
Tabular data[(a)]	Geochemistry, drill-log data and surveying data	Delimited ASCII (prefer Tab-delimited)	Standard as described below or AMIRA P431 or PPDM format	.dat
Geophysics (other than seismic)	Raw and processed located data gridded data	ASEG GDF2 ASEG GXF ER Mapper grid	–	.gdf .gxf .ers
Geophysical images	Images derived from magnetics or gravity e.g. TMI, Bouguer	TIFF (colour) PDF EPS	300 dpi, 24 bit Normal[(b)]	.tif .pdf .eps
Seismic data	Raw and processed data Navigation data	SEG Y SEG D SEG B UKOOA P1/90 SPS	–	.seg .uka .sps
	Processed sections	CGM+ format	With line number	.cgm
Petrophysical and geophysical log data	Raw and processed wireline and MWD data	DLIS, LIS LAS ASCII	As defined by latest industry standard	.lis .las .asc
	Log plots <1145 mm in length at full scale	PDF	Normal[(b)]	.pdf
	Log plots >1145 mm in length at full scale	PDF EPS	With scaling factor[(b)]	.pdf .eps
Downhole velocity data	Processed downhole velocity data	SEG Y files	–	.seg
Geo-referenced polygons and lines (derived datasets)	Maps, plans	PDF TIFF	Normal[(b)] 300 dpi, 24 bit	.pdf .tif
Text	Includes text, figures etc. normally provided in hard copy	PDF	Normal[(b)]	.pdf
Maps, plans, figures (not included in text)	Files of maps <1145 mm in length at full scale	PDF	Normal[(b)]	.pdf
	Files of maps >1145 mm in length at full scale	TIFF PDF EPS	300 dpi, 24 bit With scaling factor[(b)]	.tif .pdf .eps
Photographs (not included in text)	Core photographs, aerial photographs etc.	PNG JPG	–	.png .jpg

NOTES: (a) Where several related database files cover one theme (e.g. surveying data, drill logs, look-up tables etc.) tabular data should be submitted in a **self-extracting zip file** containing all relevant files.
(b) PDF files should be created from the original plot file where possible and a scaling factor included for plots greater than 1145 mm in length.

of standards is proposed below that will facilitate confident interpretation of statutory exploration data in the future.

The standards have been designed to allow the future user maximum flexibility and ensure that critical metadata and supporting data such as authority or look-up tables are included. Metadata are by far the most critical issue affecting digital data and will require a change in philosophy on data submission. Most companies submit metadata as part of the text of a printed report — now we propose that critical metadata are included in the 'header' to the real data. This is recommended as the report and the digital data may become separated over time and the purpose of these standards is to ensure the digital data can be used in isolation from the report and still provide essential data for intelligent interpretation.

The 'metadata' being requested in the 'file header' are data usually provided in the printed report submitted to the Department. The objective of including the metadata with the 'real' data is to remove the reliance on having to search for other data packages (i.e. the report plus the digital data) to build a complete set of data.

Generally, the preferred file format for tabular data is a 'flat file' rather than a 'relational' file system. This allows more flexibility in the format and also reduces the need for relational keys between files. However, some datasets, particularly drill logs incorporating lithological, geochemical, structural and other data, including authority and look-up tables, may have to be submitted as a series of related flat files. Where possible, formats have been devised using existing standards in industry such as SDTS, UKOOA and ANZLIC. Where relational standards such as PPDM and AMIRA P431 are in existence, the format has been structured to allow easy importation of the data to systems running on those standards.

It is expected that software vendors in the mineral exploration industry will develop user-friendly packages to enable companies to provide the data in DME formats.

Release of information

The Western Australia Department of Minerals and Energy will be making available open-file digital data as self-extracting zip files that will be supplied on request to the customer. It is planned that with the compliance of industry to the proposed standards, the use and manipulation of the data in the future will be easy to use and understandable by all.

Devonian stromatolites and exhalative mineralization, Canning Basin, Western Australia

by

P. E. Playford

Massive limestone buildups of columnar stromatolites, intergrown with barite and iron sulfides, are known from four principal localities in the Devonian reef complexes of the Canning Basin. They outcrop in the northern Emanuel Range, southeastern Pillara Range, Minnie Pool, and Pillara Spring areas of the southeastern Lennard Shelf. The stromatolite–barite–sulfide association occurs as belts from a few hundred metres to three kilometres long, 250 m wide, and 100 m thick, within Frasnian basin facies of the upper Gogo Formation and lowermost Virgin Hills Formation.

The stromatolites, when unaltered, consist of light-coloured inclusion-rich fibrous-calcite crystals, with some interspersed sediment layers, arranged in fan-shaped aggregates displaying unidirectional growth. The well-preserved microstructure of the calcite, which includes minute single-phase fluid inclusions, indicates an original calcitic (rather than aragonitic) mineralogy.

Some stromatolites have been partly or wholly altered to inclusion-free calcite, often dark in colour, in which the original stromatolitic textures are wholly or partly destroyed. The metasomatism responsible for these changes is thought to have been linked with low-temperature fluids that were responsible for associated barite and iron-sulfide mineralization.

Barite associated with the stromatolites occurs as two forms: (a) fibrous crystals filling fractures which cross-cut the fibrous calcite, and (b) fan-shaped crystal masses intergrown with stromatolites. The intergrown barite, like the stromatolites, displays textures indicative of unidirectional growth.

Dendritic iron sulfides (marcasite and pyrite) grew into cavities between stromatolite columns during the late growth phases of the stromatolite buildups. These sulfides have been oxidized to gossanous iron oxides at the surface. The outcropping stromatolite–barite–sulfide buildups are commonly cut by fissure-filling gossans, up to several metres wide and tens of metres long, in which stromatolitic structures, of probable bacterial origin, are often well displayed. Drilling in the northern Emanuel Range and southeastern Pillara Range areas shows that the gossans have formed after marcasite and (to a lesser extent) pyrite. A few small crystals of galena have been detected within some of the iron sulfides (Wallace, M., 1999, pers. comm.). Although sphalerite has not been identified, it could occur in minor amounts, as some gossans contain anomalously high zinc values (up to 7400 ppm).

The stromatolites and associated mineralization are believed to have formed during the early and middle Frasnian as cool-water sedimentary exhalative (SEDEX) deposits, during a period of abrupt backstepping of the limestone platforms. They were formed above permeable zones where water, methane, hydrogen sulfide, and mineralizing fluids were being expelled during early compaction of organic-rich shales of the Gogo Formation. Those shales have compacted by about 70% since deposition, resulting in the expulsion of large volumes of fluids, which were channeled along permeable horizons within the Gogo Formation towards the contact with the Sadler Limestone and then along that contact towards the surface, permeating and passing through the muds (Fig. 1). Synsedimentary faults in the Gogo Formation and basal Virgin Hills Formation also acted as pathways for escaping fluids.

The stromatolites and associated mineralization form bulbous masses, believed to have been precipitated by chemosynthetic bacteria below water depths of around 200 m. The main masses of the buildups apparently developed in unconsolidated mud. Some probably extended a little above the surrounding sediment, but others clearly grew downward into the mud itself, so that photosynthesis could not have been required for their development.

A transitional relationship can be seen between limestones of the stromatolite–barite–sulfide association and Gogo nodules (cannonball concretions), which are thought to have had a similar chemosynthetic bacterial origin, growing in mud just below the sediment–water interface. Small calcite spherules, also probably of bacterial origin, are closely associated with the Gogo nodules and stromatolite buildups.

A few exploration drillholes have penetrated stromatolite–barite–sulfide buildups and their associated iron-sulfide-filled fissures. Some holes encountered minor Mississippi-Valley-type (MVT) mineralization in fractures that cut the buildups and associated fissures. This MVT mineralization is thought to have occurred during the Early Carboniferous or latest Devonian, perhaps 10 million years later than growth of the stromatolite–barite–sulfide buildups and after they were covered by more than 1000 m of sediment.

Isotope studies have been carried out on the stromatolite–barite–sulfide association by Malcolm Wallace, Nicole de Kever, and Rebecca Mason of the University of Melbourne. Carbon and oxygen isotopes from inclusion-rich stromatolites and Gogo nodules occupy similar fields, with significantly lighter carbon and oxygen values than those of Devonian seawater. These values are compatible with a bacterial origin of the stromatolites and nodules. The inclusion-free stromatolites are clustered in a distinctly different field, with even lighter carbon values, but having oxygen values comparable with that of Devonian seawater. These differences may be explained by early metasomatic alteration of the inclusion-free stromatolites.

The sulfur isotopes of iron sulfides in the buildups are heavier than those of Middle to Late Devonian seawater and much heavier than those of MVT sulfides from elsewhere on the Lennard Shelf. This may be explained by early bacterial sulfate reduction in muds of the Gogo Formation, which removed lighter sulfur isotopes from the interstitial fluids.

Although it seems clear that there is no direct relationship between the early SEDEX mineralization and later MVT mineralization, both are thought to have resulted from related compaction-driven processes. The SEDEX deposits formed near the sea floor from low-temperature fluids expelled during early compaction of basinal muds, whereas the MVT deposits were precipitated at depth from hotter fluids expelled during later phases of shale compaction. Whether they represent end-member products of a continuing process has yet to be resolved.

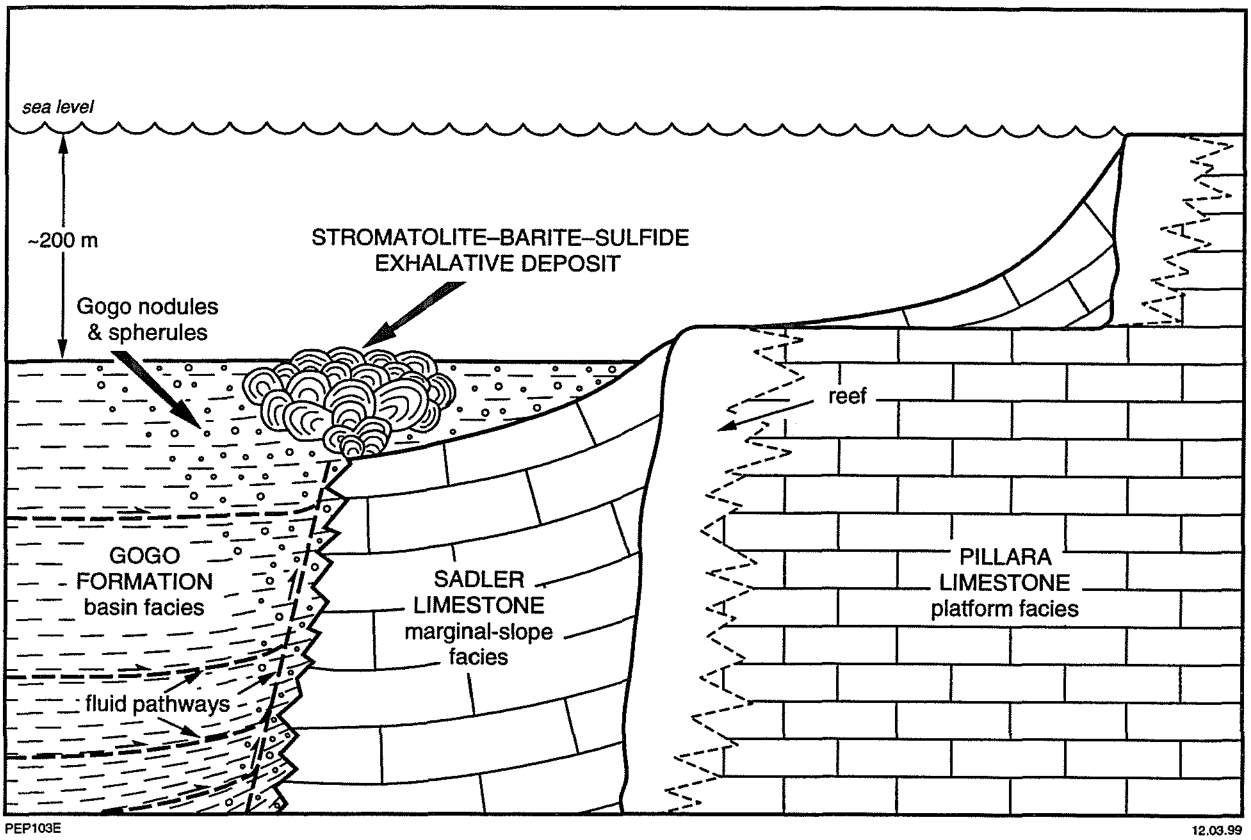


Figure 1. Diagrammatic section illustrating the origin of stromatolite–barite–sulfide exhalative (SEDEX) deposits and related nodules and spherules in the Gogo Formation

Assessing the effects of grain size on chemistry — results from the GSWA's Regional Regolith Geochemical Program, Western Australia

by

P. A. Morris

Prior to implementation of geochemical surveys, orientation programs are usually carried out to optimize the approaches to field work and analysis. In the case of regional-scale geochemical surveys involving relatively low density sampling over large areas, orientation programs may not be carried out because of limitations imposed by time and resources. Instead, a uniform approach is adopted based on published data from similar-scale surveys, and local experience in the areas under consideration. This is the case for the GSWA's regional regolith geochemical program, where regolith is sampled at a uniform density of one sample per 16 km^2, utilizing a variety of sample media, including stream sediments, sheetwash, sandplain, and lake sediments, depending on local conditions. In order to minimize the effects of heterogeneity introduced by large fragments ('nugget effect'), and avoid excessive dilution by fine-grained eolian material, the 2–0.45 mm fraction is analysed for all samples.

In order to review the appropriateness of this grain size fraction on chemistry, the <2 mm and <0.45 mm fractions of fifty-four samples from eleven 1:250 000 mapsheets have been further analysed. The mapsheets span a variety of lithologic and physiographic associations from granite–greenstones of the Archaean Yilgarn Craton, to more diverse assemblages of dominantly siliciclastic sedimentary rocks of the Capricorn Orogen. Each sample was analysed for a variety of major element-oxides and trace elements, including Au, As, Zr, and Cr. In comparing the <2mm and 2–0.45 mm fractions, the highest Au concentrations are found in the 2–0.45 mm fraction for more than 80% of samples, with no apparent control in terms of mapsheet (i.e. geology), regolith type, or sample medium. In contrast, for more than 70% of samples, SiO_2 is higher in the <2 mm grain size fraction, although many samples plot close to a 1:1 line. This suggests that (a) Au is found as either coarse-grained particulate material, or as fine-grained material deposited on coarse-grained fragments, and (b) higher SiO_2 in the < 2 mm size fraction results from eolian input or concentration of quartz through loss of more labile components. Eolian input is more likely, as indicators of weathering are similar for both grain size fractions, and increases of up to 50% in SiO_2 in the <2 mm size fraction are inconsistent with the stability of quartz in the weathering environment. Plots showing the ratios of analyte concentrations in the respective grain size fractions can be used to further evaluate changes in chemistry according to grain size. In Figure 1, the variable AC is the ratio of the analyte concentration in the <2 mm fraction to the concentration in the 2–0.45 mm fraction. In the case of Zr and SiO_2, analyses plot at either AC(Zr) and AC(SiO_2)>1 (quadrant 2: eolian input of quartz and zircon in the fine-grain size fraction) or AC(SiO_2)=1 and AC(Zr)>1 (join of quadrants 1 and 2: no eolian input of quartz, but eolian input of zircon). In contrast, when Cr is compared to SiO_2, analyses show increase in Cr with no addition of SiO_2 in the <2 mm size fraction, or no change in Cr or SiO_2, or some dilution of Cr by addition of SiO_2. The implication here is some mechanical breakdown of

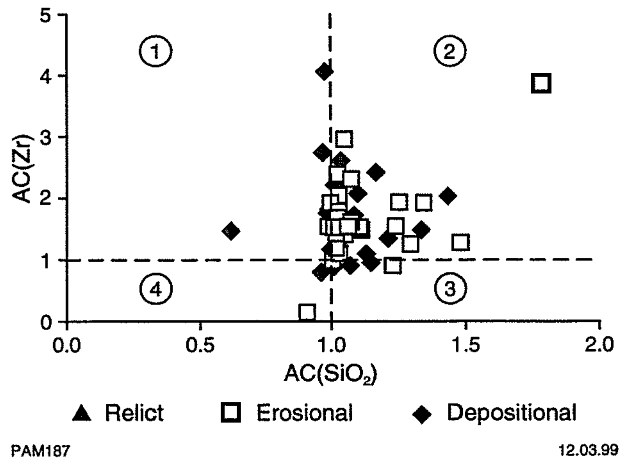


Figure 1. AC is the concentration of either Zr or SiO_2 in the <2 mm fraction divided by the respective concentration in the 2–0.45 mm fraction (AC (Zr) and AC(SiO_2) respectively) for regolith samples according to regolith type. Circled numbers are quadrant designations, discussed in text

chromite leading to a relatively higher concentration in the <2 mm size fraction, or no change at all, or dilution of chromite in the <2 mm size fraction by addition of eolian-sourced quartz.

Arsenic is a commonly used pathfinder element for Au mineralization. The behaviour of As in relation to SiO_2 is in marked contrast to that of either Zr or Cr, in that As is lower (rarely higher) in the <2 mm size fraction (with no change in SiO_2), or is diluted by addition of quartz.

The behaviour of Zr, Cr and As in relation to SiO_2 illustrates no consistent pattern in regolith chemistry according to either sample medium, or regolith type, or mapsheet (geology). Within-mapsheet variation is commonly observed. The only element to show consistent behaviour is Au, which appears to be in higher concentrations in the 2–0.45 mm size fraction. Thus, no one grain size fraction is suitable for all analytes examined in the GSWA's program. This, taken in conjunction with the need for rapid release of data, and maximizing the use of resources, validates the current approach of using the 2–0.45 mm grain size fraction for multielement analysis in the GSWA's Regional Regolith Geochemical Program.

Localized metasomatic alteration and mineralization of the Mount Belches Formation, southern Eastern Goldfields, Western Australia

by

M. G. M. Painter

Orogenic gold mineralization hosted by the Mount Belches Formation is located about 80 km east-southeast of Kalgoorlie. Mapping of the MOUNT BELCHES 1:100 000 sheet has revealed metasomatic alteration, similar to that at known deposits, scattered throughout the area. Many of these alteration zones occur in areas that are structurally favourable for gold mineralization.

The Mount Belches Formation (formerly Mount Belches Beds) comprises a sequence of metamorphosed greywacke with subordinate mudstone, banded iron-formation (BIF), Fe-mudstone and chert. Locally abundant sedimentary structures and features, which include Bouma sequences, ripples, cross-laminae, channels and soft-sediment deformation, are minimally affected by lower amphibolite facies metamorphism. Owing to the degree of metamorphism, dominant rock types are classified as psammites and psammopelites; pelites are relatively uncommon. Pelitic portions of beds are generally biotitic (Dunbar and McCall, 1971) but andalusite, sillimanite, garnet and staurolite are observed locally. The formation has been interpreted as a submarine fan of flysch facies (Dunbar and McCall, 1971).

The Mount Belches Formation forms a regional domal anticline that is probably due to interference of F_1 and F_2 folds (Fig. 1). Thrusting during D_1 resulted in northward displacement of a thrust sheet or duplex. A broad east–west trending arch resulted, with a northerly exposure of BIF most probably representing a frontal recumbent fold. S_1 is locally observed and is generally layer parallel. In the centre of the map sheet, S_1 is approximately flat lying and is locally crenulated by S_2. Peak metamorphism accompanied east–west shortening during D_2, resulting in the distinctive chevron folds of the BIF unit and a pervasive northerly to north-northwesterly trending subvertical S_2 foliation. Isoclinal folds adjacent to the Randalls Fault are probably the result of later movement during D_3 and D_4 (Witt, W., 1998, pers. comm.). Using aeromagnetic data in conjunction with field observations, major fault traces have been realigned, and several fault jogs have been interpreted along the Mount Monger and Cowarna Faults (Fig. 1).

Orogenic gold mineralization at Randalls and Karnilbinia represents the two major occurrences of gold in the Mount Belches Formation. Up to March 1997, 3 222 700 t of ore at 3.2 g/t yielded 10 300 kg of gold from these deposits. The mines are currently inactive. Economic gold mineralization is hosted by BIF units in post-D_2 shallow-dipping quartz veins and associated sulfidic alteration haloes. This mineralization is located in the overturned anticlinal hinge zones and immediately adjacent eastern limbs (Newton et al., 1998).

Alteration style within the mines is dependent upon host lithology. The BIF hosts an assemblage of magnetite, cummingtonite/grunerite, hornblende, actinolite, biotite, chlorite, carbo-nate and iron sulfides. Psammites above and below the BIF unit host an alteration assemblage of magnetite, quartz, chlorite and grunerite, with biotite porphyroblasts and minor Ca-amphiboles and carbonates. These alteration zones are distinguished by a lath or rosette habit of the amphiboles and the interstitial granuloblastic quartz (Newton et al., 1998).

Regionally, two distinct styles of alteration are apparent. Most common is a quartz–grunerite(–Ca-amphibole) assemblage, similar to that described for alteration of psammites at Randalls and Karnilbinia. It occurs at a variety of scales, from a few millimetres each side of a quartz veinlet to diffuse patches several metres across to areas several kilometres wide. Altered zones are dispersed irregularly throughout the area (Fig. 1). Less abundant is alteration with a quartz–carbonate(–chlorite–magnetite) assemblage. Such alteration has been observed only as diffuse patches south of Karnilbinia and in greenstones in the Bulong Anticline of the Gindalbie terrane (Fig. 1).

Alteration assemblages such as these are considered part of a continuum that represents metasomatism under varied conditions. Carbonate-bearing alteration represents upper greenschist facies alteration whereas the amphibolitic alteration represents lower amphibolite facies alteration (Groves et al., 1995).

Essential parameters for orogenic gold mineralization include competency contrasts, a localized low-stress

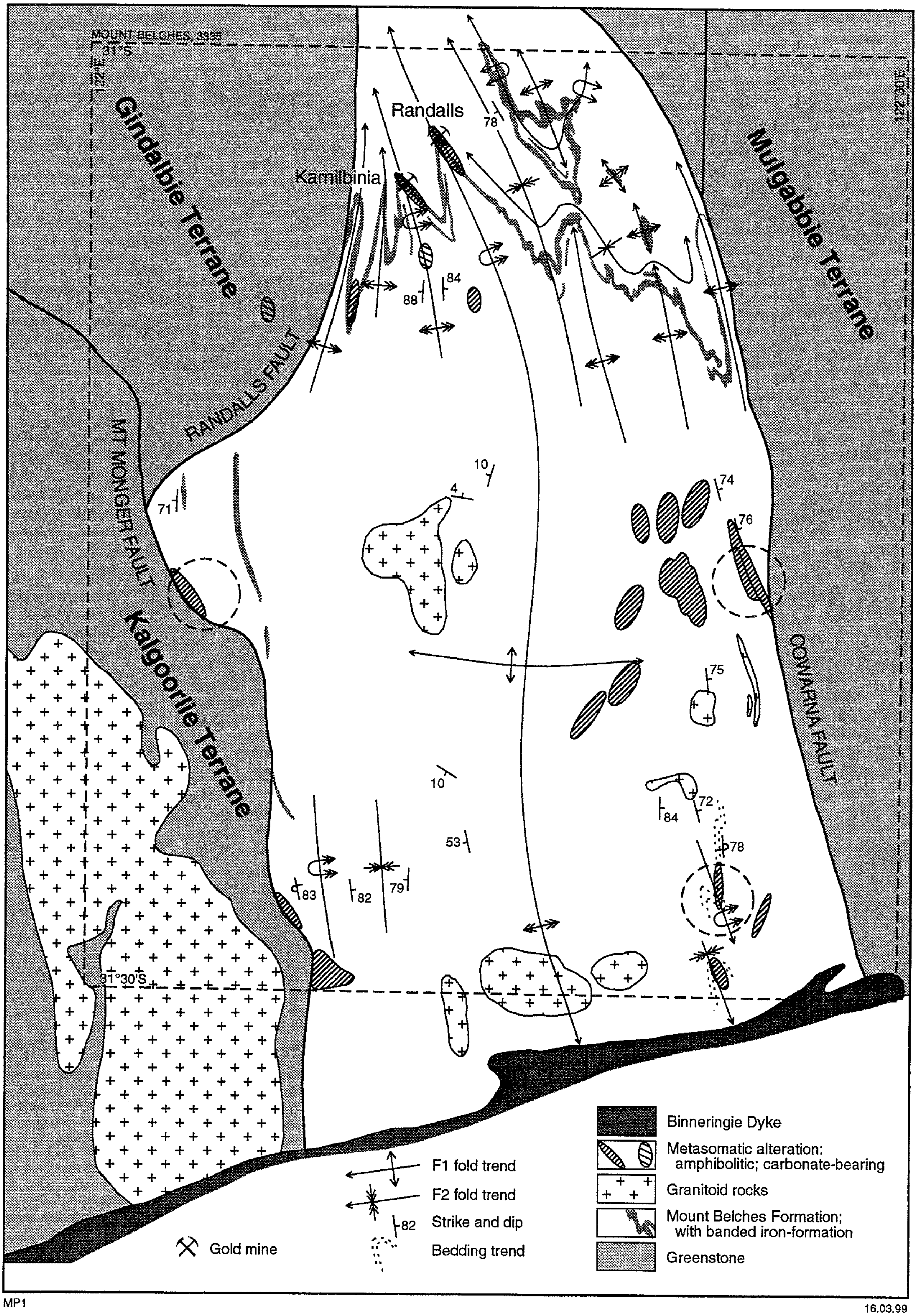


Figure 1. Interpreted Archaean geology of the Mount Belches Formation (after Swager, 1995), showing structure and alteration zones. Dashed outline represents the boundary of the Mount Belches 1:100 000 sheet

regime and rock interaction with low salinity, and auriferous $H_2O–CO_2(–CH_4)$ fluids (Groves et al.,1995). At Randalls and Karnilbinia, these criteria are met because the ore is associated with BIF horizons within a psammite sequence, hinge zones of overturned anticlines, and alteration. Elsewhere, zones of intense hydrothermal alteration often coincide with sites of structural dilatancy. Such sites include the fault jogs on the Mount Monger and Cowarna Faults, and the large-scale, south-plunging, overturned, parasitic folds on the regional F_2 anticline (e.g. Fig. 1 — circled areas). Although few BIF units are apparent to the south, other units, such as sandstones in the poorly understood facies architecture of the Mount Belches Formation, could provide the necessary competency contrasts. The broad alteration zones in the east-central area of the map sheet are deeply weathered and controls on their distribution remain obscure.

Given the coincidence of these features, there is potential for orogenic gold mineralization elsewhere in the Mount Belches Formation. The lack of BIF to the south, however, suggests that any such deposits, should they exist, would not resemble the Randalls and Karnilbinia deposits, but would instead be hosted by different lithologies.

References

DUNBAR, G. J., and McCALL, G. J. H., 1971, Archaean turbidites and banded ironstones of the Mt Belches area (Western Australia), Sedimentary Geology, 5, p. 93–133.

GROVES, D. I., RIDLEY, J. R., BLOEM, E. M. J., GEBRE-MARIAM, M., HAGEMANN, S. G., HRONSKY, J. M. A., KNIGHT, J. T., McNAUGHTON, N. J., OJALA, J., VIELREICHER, R. M., McCUAIG, T. C., and HOLYLAND, P. W., 1995, Lode-gold deposits of the Yilgarn block: products of Late Archaean crustal-scale overpressured hydrothermal systems, *in* Early Precambrian Processes *edited by* M.P COWARD and A.C. RIES: Geological Society Special Publication No. 95, p. 155–172

NEWTON, P. G. N., SMITH, B., BOLGER, C., and HOLMES, R., 1998, Randalls gold deposits, *in* Geology of Australian and Papua New Guinean Mineral Deposits (*edited by* D. A. BERKMAN and D. H. MACKENZIE): Melbourne, The Australasian Institute of Mining and Metallurgy, p. 225–232.

SWAGER, C. P., 1995, Geology of the greenstone terranes in the Kurnalpi–Edjudina region, southeastern Yilgarn Craton: Western Australia Geological Survey, Report 47, 31p.

A refined stratigraphic framework for the Neoproterozoic: advances in Officer Basin correlation, Western Australia

by

K. Grey

Evaluation of hydrocarbon potential requires adequate stratigraphic and structural control. Neoproterozoic Officer Basin correlations and relationships to the Centralian Superbasin and Adelaide Rift Complex are constrained by lack of outcrop, limited seismic coverage, and sparse drillholes. However, the stratigraphy is being refined by the integration of stromatolite biostratigraphy, palynology, and isotope chemostratigraphy. This approach has improved correlation quality, resolved some Australia-wide problems, and provided a framework for Rodinia reconstructions.

Outcrops and drillcore were sampled for stromatolites and palynology and fossil data were reviewed as part of GSWA's Interior Basins Petroleum Initiative. Both stromatolites and palynomorphs produced consistent results, indicating correlation between the Officer Basin succession, and the Savory and Tarcunyah Groups (formerly part of the Yeneena Group). Correlation has been extended to the rest of the Centralian Superbasin and Adelaide Rift Complex (Fig. 1). Rationalization of stratigraphic terminology continues.

Stromatolite biostratigraphy has on occasion been disparaged because of supposed lack of environmental controls. However, effective stromatolite correlation needs to be based on adequate systematic studies and identification to form (i.e.= species level). When this has been done, Australian Neoproterozoic stromatolite taxa demonstrate restricted time distributions. In the Officer Basin, *Basisphaera irregularis* changes from club-shaped to tabular as conditions shallow, but its microstructure remains constant and characterizes it as *Bas. irregularis*. Thus, an individual taxon can retain inherent characteristics regardless of environmental change. Some distributions are environmentally controlled. For example, *Acaciella australica* predominates in sediment-starved carbonate environments and *Bas. irregularis* is rare but becomes more dominant as clastic-sediment input and energy regime increase. Different stromatolite associations occur in similar, but younger, sediment-starved/high-energy environments, so a taxon plots only once on range charts. Such observations are inconsistent with an overriding environmental control, and indicate significant biostratigraphic influence.

Stromatolites are present in all four Neoproterozoic Supersequences in the Centralian Superbasin. Two assemblages occur in Supersequence 1 (basal Centralian Superbasin succession). The older, *Acaciella australica* Assemblage, is dominated by *A. australica* and *Bas. irregularis*. It occurs in the Browne, Woolnough, and Skates Hills Formations. The same assemblage occurs in the Bitter Springs Formation (Amadeus Basin), Yackah beds (Georgina Basin), Ruby Plains Group (Wolfe Basin), and Callanna Group (Adelaide Rift Complex). The younger, *Baicalia burra* Assemblage (upper Supersequence 1), is dominated by *B. burra*, but also contains *Tungussia wilkatanna*, *Conophyton* new form, and a pseudocolumnar stromatolite. This assemblage is present in unnamed carbonates near the Eagle Highway, the Neale Formation and in NJD 1 near Neale Junction, Kanpa Formation in Hussar 1, and the Tarcunyah Group at Constance Headland. It was previously recorded from the Burra Group (Adelaide Rift Complex), and as diamictite clasts in Tasmania, but there are no known equivalents in central Australia. Correlation between the Callanna Group and Bitter Springs Formation is more likely than between the Burra Group and Bitter Springs Formation as in previous interpretations.

Supersequence 2 and 3 stromatolites may eventually prove useful for intrabasinal correlation, but most have restricted geographical distributions. However, incipient columns of *Elleria minuta*, characteristic of the Amadeus Basin Marinoan cap dolomite, were identified in a 50 cm-thick dolomite horizon above a diamictite in Empress 1/1A. Near the top of Supersequence 3, *Tungussia julia* occurs in the Wonoka Formation (Adelaide Rift Complex), Julie Formation (Amadeus Basin), and Egan Formation (Kimberley area). A few forms are present in Supersequence 4, but again localities remain limited.

Palynology is increasingly significant in Centralian Superbasin correlation and provides biostratigraphic control as well as indicating palaeoenvironment and

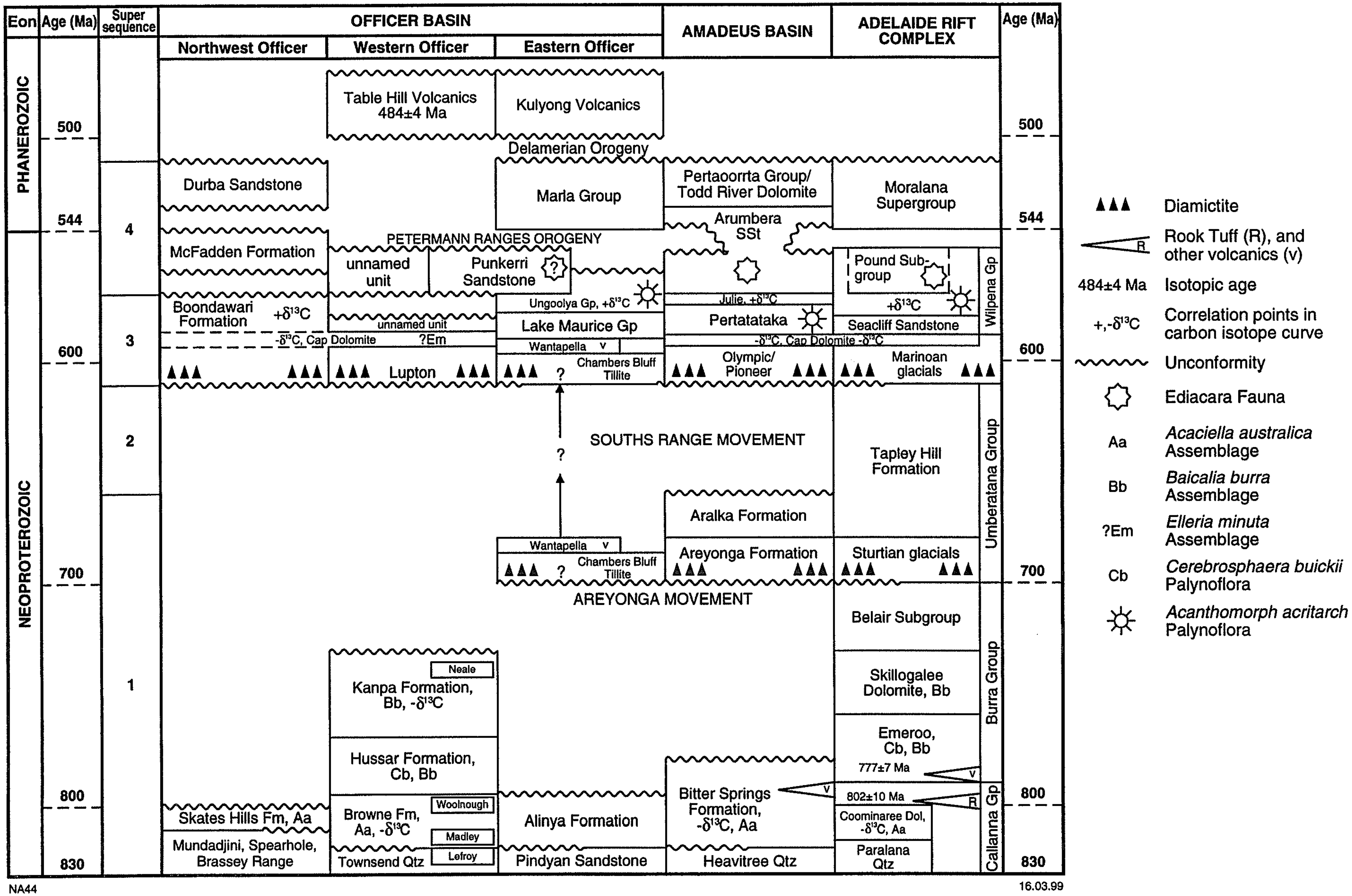


Figure 1. Stratigraphic correlation of the Officer and Amadeus Basins and Adelaide Rift Complex

thermal maturity. Supersequence 1 is dominated by leiospheres, filaments and mat fragments; all conservative, long-ranging species that have simple morphologies. However, a few morphologically distinct species have short ranges. For example, *Cerebrosphaera buickii* is a marker species for upper Supersequence 1, and in the Officer Basin consistently first appears about the middle Hussar Formation. It occurs at about the same level in the Burra Group (Adelaide Rift Complex), but has not been recognized in Amadeus Basin drillholes. Supersequence 2 assemblages are poorly known throughout Australia, but middle Supersequence 3 is characterized by a highly distinctive, morphologically complex, acanthomorph acritarch assemblage. Four assemblage zones allow correlation between southern and central Australia, but have not so far been observed in the western Officer Basin. Upper Supersequence 3 and Supersequence 4 mark a return to leiosphere assemblages. However, Supersequence 4 is characterized by the development of the Ediacara fauna.

Neoproterozoic correlations based on isotope chemostratigraphy are well advanced in central and southern Australia (Calver, 1995; Calver and Lindsay, 1998; Hill 1998). In particular, the $\delta^{13}C$ curve is very distinctive and, especially when combined with other curves (such as $\delta^{18}O$ and $^{87}Sr/^{86}Sr$), allows global correlation. Isotope chemostratigraphy provides an independent method of testing biostratigraphic correlations.

Biostratigraphic schemes derived from outcrop and existing drillholes were tested by stratigraphic drillhole GSWA Empress 1/1A. The 1624.6 m drillhole contains over 70 stromatolite horizons, with the *Baicalia burra* Assemblage present in the Kanpa and upper Hussar Formations and the *Acaciella australica* Assemblage in the Browne Formation. *Cerebrosphaera buickii* first appears in the middle Hussar Formation. Both stromatolites and palynomorphs fit the field-derived biostratigraphic models.

Empress 1/1A contains numerous carbonate horizons, and presented an opportunity to test biostratigraphic results using isotope chemostratigraphy (Walter and Hill, 1999). The $\delta^{13}C_{carb}$ values support biostratigraphic correlations. In particular, the values from the Browne Formation matched those of the Bitter Springs Formation and Callanna Group, and those from the Kanpa Formation matched the Burra Group. Additionally, the 'cap dolomite' values from Empress 1/1A are consistent with those obtained from Marinoan cap dolomites elsewhere in the Centralian Superbasin.

Improved correlation should enhance both hydrocarbon and mineral exploration in Neoproterozoic successions, and provide a better framework for model development for hydrocarbon prospectivity in the Officer Basin. It should also increase understanding of the stratigraphic and tectonic setting of the Centralian Superbasin and Adelaide Rift Complex.

References

CALVER, C. R., 1995, Ediacarian isotope stratigraphy of Australia: Sydney, Macquarie University, PhD thesis (unpublished).

CALVER, C. R., and LINDSAY, J. F., 1998, Ediacarian sequence and isotope stratigraphy of the Officer Basin, South Australia: Australian Journal of Earth Sciences, v. 45, p. 513–532.

HILL, A. C., 1998, Isotope stratigraphy of the mid-Neoproterozoic of Australia: Sydney, Macquarie University, PhD thesis (unpublished).

WALTER, M. R. and HILL, A. C., 1999, Carbon isotope stratigraphy of Empress 1/1A, Supersequence 1, Western Officer Basin. Western Australia Geological Survey, S-series, S20424 A8 (unpublished).

The new 1:2 500 000-scale State geological map of Western Australia

by

J. S. Myers and R. M. Hocking

A new 1:2 500 000-scale geological map of Western Australia was compiled and printed during 1998 (Myers and Hocking, 1998). The map provides a new interpretation of the geology of Western Australia based on field mapping and geochronology by the Geological Survey of Western Australia (GSWA), regional aeromagnetic and gravity data, and recent publications from various sources. The map incorporates many new features on the map face and provides much more information than its 1988 predecessor. The main features are listed below. The 1998 printed map is also available digitally, in Microstation DGN format and ArcInfo format, and can be provided as Map Info export files on request. The digital formats enable the geology to be interrogated and integrated with data on mineral deposits, mineral exploration, and mining tenements. The 1998 map has already been simplified and combined with information on mineral deposits, and has been published as an atlas and gazetteer in which deposits can easily be located by type, name or area (GSWA, 1999). The 1998 map will form the basis for future GSWA index maps.

Large areas of the 1998 geological map are based on new detailed mapping by the GSWA. Since 1988, new concepts and revised geology have arisen out of the Eastern Goldfields, Glengarry, Southern Gascoyne, Rudall, Pilbara, Kimberley, Earaheedy, Western Margin, and Interior Basins projects. The map also contains a substantial amount of new structural and tectonic interpretation, gained through the integration of geological mapping with aeromagnetic and gravity data. Many observations and interpretations appear for the first time on this map — new information was added, and the map updated, until early November 1998.

The geology is subdivided and portrayed in a similar manner to the 1988 map, with largely the same colour scheme and style of legend. Precambrian geology is displayed as either lithostratigraphic packages of formations and groups that are generally relatively little deformed or metamorphosed, or by lithology in belts of generally more highly deformed and metamorphosed rocks. New geochronological results obtained during the past ten years have enabled the ages of Precambrian geological units to be defined with greater precision, and this information has been used to place most Precambrian rock units into time slots of 100 million years. Phanerozoic geology is presented as major depositional rock packages, but like the Precambrian is more finely subdivided on this map than the 1988 edition. Interestingly, where recent work has cast doubts on the assumed age of some successions, the age of some Phanerozoic rocks is shown with more latitude than in 1988.

The main new features of the 1998 State geological map are:

- Completely new compilation of the geology of the eastern part of the Yilgarn Craton, the southern part of the Capricorn Orogen, the Pilbara granite–greenstone terrane, the Rudall portion of the Paterson Orogen, and the west and east Kimberley, all largely based on new mapping for 1:100 000-scale map sheets. The Perth and Carnarvon Basins have been revised substantially after reassessments by the Petroleum Initiatives Group within GSWA and limited remapping.
- Geological structure of Western Australia substantially reinterpreted, based on integration of geological mapping with aeromagnetic and gravity data.
- Interpretation of the gross geological structure of crystalline basement beneath the the Canning, Officer and Eucla Basins.
- Dynamics of major fault movements indicated, and fault systems linked at both near-surface and subsurface levels. The major offshore structural fabric around Western Australia has been interpreted and compiled from both published and unpublished sources including GeoSat and ERS-1 satellite data, and linked to onshore structures.
- Reinterpretation of the eastern part of the Albany–Fraser Orogen based on new geological reconnaissance mapping, geochronology, and geophysics.
- Major lithostratigraphic revisions in the southern Capricorn Orogen and the Centralian Superbasin.

- Dolerite dykes interpreted from aeromagnetic data as well as from mapped exposures.
- Contours showing the thickness of Neoproterozoic sedimentary rocks in the Officer Basin, and the thickness of Phanerozoic sedimentary rocks offshore and in most onshore basins.
- Location of the pre-Miocene palaeodrainage systems.
- Elimination of the term Tertiary, following IUGS recommendations, and using Cainozoic series (Miocene etc.) directly.

The geology of Western Australia reveals a long dynamic history of repeated generation, aggregation and dispersal of crustal fragments. The boundaries between these crustal fragments remained zones of crustal weakness in which the rocks were intermittently folded, fractured and overlain by sedimentary rocks. These zones (orogenic belts) provided important environments for the development of mineral deposits, and the location and structure of many mineral deposits are related to the tectonic evolution of these belts.

The oldest crustal fragments (Pilbara and Yilgarn Cratons) were themselves formed by the amalgamation of a number of older pieces of crust, and the location of mineral deposits such as gold are related to the older boundaries and associated fracture zones within these cratons. The Pilbara and Yilgarn Cratons were joined along the Capricorn Orogen at c. 1800 Ma to form the West Australian Craton, and this was joined at c. 1300 Ma with the North Australian Craton, along the Paterson Orogen, and a combined south Australian–East Antarctic continent called the Mawson Craton, along the Albany–Fraser Orogen.

An overlay of current mineral exploration and mining tenements on the geological map shows that, while there is substantial interest in the geology of Western Australia, some geological units that could have significant mineral potential are currently underexplored. Most of the greenstones of the Archaean Pilbara and Yilgarn Cratons are currently being explored, and there is widespread exploration along the margins of the Capricorn Orogen, and within the Halls Creek and Paterson Orogens. Exploration in especially intense in the Albany–Fraser Orogen, a region that until recently was relatively little explored. Areas currently receiving little attention include: the Archaean Fortescue flood basalts of the Pilbara Craton and Palaeozoic Antrim Plateau flood basalts in the east Kimberley (potential hosts to Noril'sk-type nickel deposits), the Gascoyne Complex of the Capricorn Orogen and overlying Bangemall Basin (potential gold and base metals), part of the Paterson Orogen, and the eastern and southern parts of the Albany–Fraser Orogen.

References

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1999, Western Australia atlas of mineral deposits and petroleum fields 1999: Western Australia Geological Survey, 33p.

MYERS, J. S., and HOCKING, R. M., 1998, Geological map of Western Australia, 1:250 000 (13th edition): Western Australia Geological Survey.