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Early Earth evolution: evidence from the 3.5–1.8 Ga geological history of the Pilbara region of Western Australia

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The Pilbara region of Western Australia is one of only two areas on Earth – the other being the Kaapvaal Craton of southern Africa – that contain well preserved, near-continuous geological records of crustal evolution from the Paleoarchean into the late Paleoproterozoic. The Pilbara is famous for hosting fossil evidence of early life (stromatolites and microfossils), and for containing a record of the early Archean atmosphere. The geological record extends from granite–greenstone terranes and overlying clastic basins of the 3.53–2.83 Ga Pilbara Craton, across a major unconformity, to a series of 2.78–1.79 Ga volcanic and sedimentary successions. Between 3.53–3.23 Ga, a succession of mantle plume events formed a thick volcanic plateau on older continental crust, remnants of which include enclaves of c. 3.6 Ga granitic gneiss and abundant 3.8–3.6 Ga inherited and detrital zircons. During each of the plume events, the volcanic plateau was intruded by crustally-derived granitic rocks, leading to vertical deformation by partial convective overturn. By 3.23 Ga, these processes had established thick continental crust that was then rifted into three microplates separated by c. 3.2 Ga basins of oceanic crust. Subsequent plate tectonic processes to 2.90 Ga included subduction, terrane accretion, and orogeny. From 2.78–2.63 Ga the northern Pilbara Craton was affected by minor rifting, followed by deposition of thick basaltic formations separated by felsic volcanic and sedimentary rocks (Fortescue Basin). Rifting in the southern Pilbara resulted in progressively deepening marginal basin sedimentation, including thick units of banded iron formation (Hamersley Basin: 2.63–2.45 Ga). At c. 2.45 Ga, sedimentation in the southern Pilbara changed to a mixed assemblage of clastic and carbonate sedimentary rocks of the Turee Creek Basin, including one unit of glacial diamictites. Deposition of the unconformably overlying 2.21–1.79 Ga Wyloo Group in the Ashburton Basin followed the Ophthalmian Orogeny, and all of these rocks were deformed by the Panhandle (c. 2 Ga) and Capricorn (c. 1.78 Ga) orogenies.

Introduction

The Pilbara region of Western Australia is one of only two areas in the world – the other being the Kaapvaal Craton of southern Africa – that provides extensive exposures of well preserved Paleoarchean–late Paleoproterozoic crust from which extensive information about the evolution of crustal processes, the biosphere and atmosphere has been obtained. The Pilbara contains three major Archean–Paleoproterozoic tectonic divisions: (1), the Pilbara Craton, composed of early crust (3.80–3.53 Ga), granite-greenstone terranes (3.53–3.07 Ga), volcanosedimentary basins (3.05–2.93 Ga), and post-orogenic granites (2.89–2.83 Ga); (2), the Fortescue, Hamersley, and Turee Creek basins (2.78–2.42 Ga), composed of a thick succession of interbedded clastic and chemical sedimentary rocks and volcanic rocks; and (3), the Ashburton Basin (2.21–1.79 Ga), composed of the volcano-sedimentary Wyloo Group.

From 1990 until 2007, the first two of these divisions were combined as the 'Pilbara Craton' (Trendall, 1990) on the grounds that there had been a continuum of depositional and igneous events from Paleo- to Mesoarchean granite-greenstones (prior to 1990 referred to as the 'Pilbara Block' in the N Pilbara) to the Proterozoic Turee Creek Group. Accordingly, it was considered that 'tectonic stability' (defining establishment of a craton) had not been attained until 2.4 Ga. However, a major geological mapping project, conducted jointly by the Geological Survey of Western Australia and Geoscience Australia between 1995 and 2002 (Huston et al., 2002a), provided a much improved geological understanding of the craton (Van Kranendonk et al., 2002, 2007a; Huston et al., 2002b). Van Kranendonk et al. (2006) revised the lithostratigraphy and tectonic units of the Paleoarchean and Mesoarchean rocks, and used the name 'Pilbara Craton' to encompass only units older than the Fortescue Group (the lowermost stratigraphic group of the Hamersley Basin). Hickman et al. (2006) explained that the change had been made because the last major deformation event to affect the granite-greenstones of the craton occurred at 2.90 Ga, after which there had been a c.130 Myr period of crustal stability (apart from the intrusion of post-orogenic granites). In 2006, the Fortescue, Hamersley, and

Turee Creek groups of the Mount Bruce Supergroup were still included within the 'Hamersley Basin', but Tyler and Hocking (2008) ascribed the succession to the Fortescue, Hamersley, and Turee Creek Basins (see also Hickman et al., 2010). The status of the Ashburton Basin has not changed since it was described by Thorne and Seymour (1991).

Pilbara Craton

Regional gravity and magnetic data indicate that the Pilbara Craton

granites between 2.89–2.83 Ga (Split Rock Supersuite) the craton remained stable until c. 2.78 Ga.

Early crust (3.80–3.53 Ga)

The Warrawagine Granitic Complex (Figure 1) includes enclaves of 3.66–3.58 Ga biotite tonalite gneiss within younger granodiorite and monzogranite. Farther W, in the Shaw Granitic Complex, xenoliths of 3.58 Ga gabbroic anorthosite (McNaughton et al., 1988) occur within 3.43 Ga granitic rocks. Many Paleoarchean and Mesoarchean siliciclastic formations contain abundant 3.8–3.6 Ga detrital zircons, indicating erosion of crust up to 300 Myr older than the East Pilbara Terrane (Hickman et al., 2010). The pre-3.53 Ga crust or mantle sources for rocks of the East Pilbara Terrane is also supported by Nd-isotopic data (Jahn et al., 1981; Gruau et al., 1987; Bickle et al., 1989; Van Kranendonk et al., 2007a, b; Tessalina et al., 2010). Champion and Smithies (2007) provided evidence that most pre-3.3 Ga granites of the Pilbara Craton were sourced through infracrustal melting of material that was older than 3.5 Ga.

East Pilbara Terrane (3.53–3.23 Ga)

The 3.53–3.23 Ga East Pilbara Terrane (Figures 2 and 3) provides the world's most complete record of Paleoarchean crustal evolution. Stratigraphy, structure, geochronology, and geochemistry collectively testify that the evolution of this terrane was dominated by volcanism, magmatic intrusion, and deformation during repeated episodes of heating and melting of underlying older crust (including felsic crust) and mantle over 300 Myr (Van Kranendonk et al., 2002, 2007a, b; Smithies et al., 2005b).

The 3.53–3.23 Ga Pilbara Supergroup of the East Pilbara Terrane is predominantly volcanic (Figure 4) and 15–20 km thick. Thick partial sections of this succession are recognized in almost all greenstone belts of the terrane, except in the NW where younger greenstones are preserved. The three component groups (Warrawoona, Kelly, and Sulphur Springs) of the Pilbara Supergroup are separated by two major erosional unconformities (Figure 4; Buick et al., 1995, 2002; Van Kranendonk et al., 2002). The time gap between the Warrawoona and Kelly groups was c. 75 Myr (3.427–3.350 Ga), and the gap between the Kelly and Sulphur Springs groups was c. 60 Myr (3.315–3.255 Ga). In both cases, the long pause in volcanic activity was preceded by deformation and metamorphism, and accompanied by subaerial erosion and deposition of clastic sediments. Shallow-water sediments between the Warrawoona and Kelly groups are preserved as the Strelley Pool Formation (up to 1 km thick; Van Kranendonk, 2010a), whereas siliciclastic rocks of the Leilira Formation (up to 3.9 km thick; Van Kranendonk and Morant, 1998) occur at the base of the Sulphur Springs Group.

Where best preserved, the Pilbara Supergroup is composed of eight ultramafic-mafic-felsic volcanic cycles (Figure 4). Geochronology on the felsic formations of successive cycles, and on contemporaneous granitic intrusions, some of which are subvolcanic (Hickman, 2012), indicates that most of the cycles spanned no more than 10–15 Myr; these cycles are interpreted to have resulted from successive mantle plume events (e.g., Arndt et al., 2001; Van Kranendonk et al., 2007a, b; Smithies et al., 2005b).

A characteristic feature of the terrane is the regional outcrop pattern of granitic domes separated by arcuate belts of volcanosedimentary rocks (greenstones) visible on geological maps (Figures 1, 2 and 3) and satellite imagery that has been variously described as "dome-and-syncline",ynTe i1,nyncorcline",ynTeolcanic

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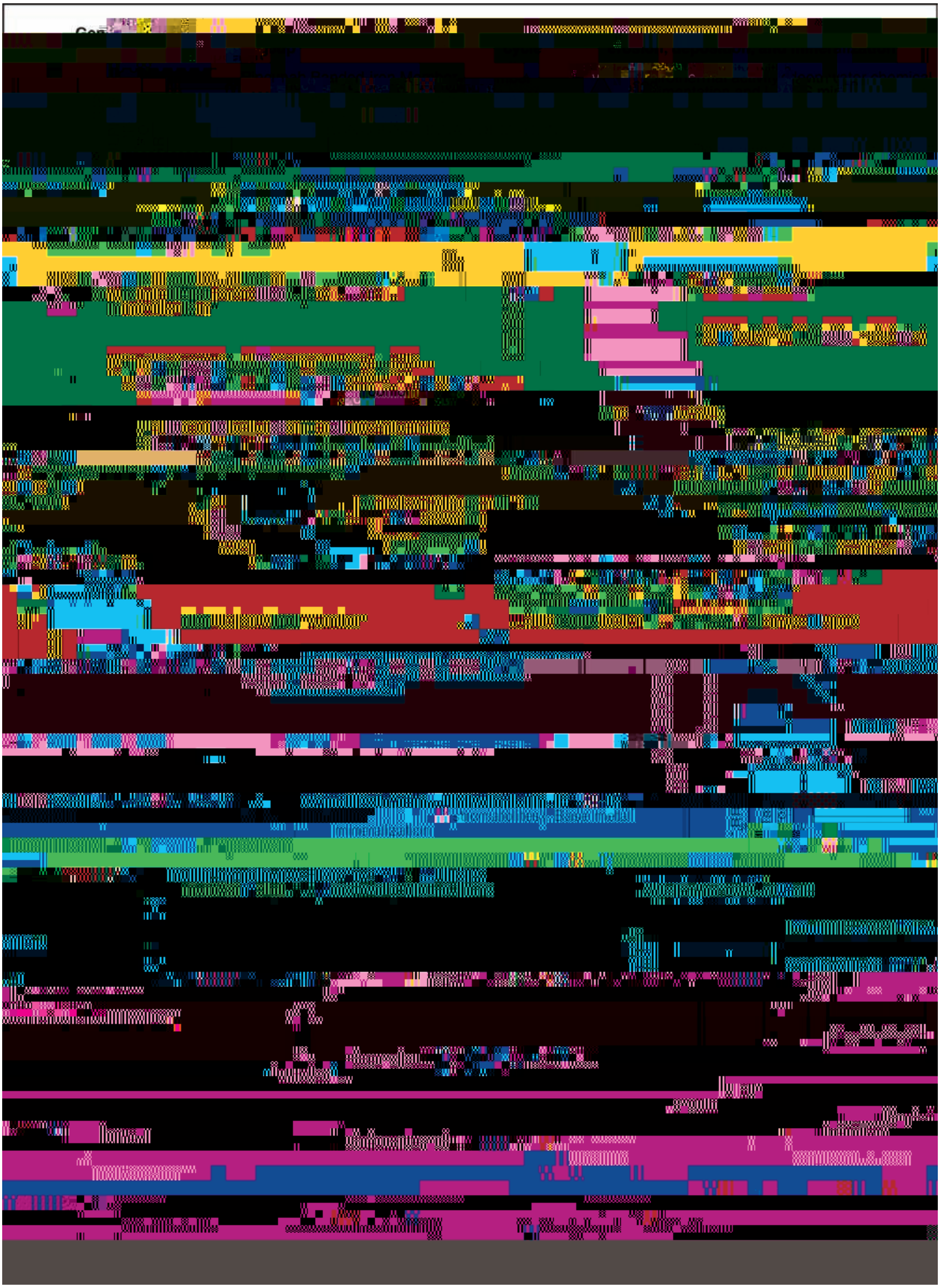

the East Pilbara Terrane (Hickman, 2001, 2004; Hickman et al., 2010; Van Kranendonk et al., 2010). This tectonomagmatic event, referred to as the Prinsep Orogeny, marks the accretion of the Karratha, Regal and Sholl terranes to form the West Pilbara Superterrane, and collision of this with the East Pilbara Terrane (Van Kranendonk et al., 2007a, 2010).

De Grey Superbasin

The De Grey Superbasin unconformably overlies the East Pilbara Terrane and the West Pilbara Superterrane. It is composed of four basins: the Gorge Creek Basin (3.05–3.02 Ga), Whim Creek Basin (3.01–2.99 Ga), Mallina Basin (3.2–2.94 Ga), and the Mosquito Creek Basin (2.99–2.90 Ga).

The regionally extensive Gorge Creek Basin is composed of the Gorge Creek Group, which in most areas consists of basal conglomerate and sandstone overlain by a 1,000 m-thick unit of BIF, chert, and black shale (Cleaverville Formation). Deposition was initially in shallow-water, and included evaporite and fluviatile deposits (Sugitani et al., 1998). Deposition of the group followed widespread erosion after the 3.07 Ga Prinsep Orogeny, and was probably developed in response to post-orogenic crustal relaxation and subsidence.

The 3.01–2.99 Ga Whim Creek Basin is located immediately to the SE of the Sholl Shear Zone and contains the Whim Creek Group of volcanic, intrusive, and volcaniclastic rocks. Reactivation of this shear zone by N–S convergence between 3.01–3.00 Ga resulted in transpressional, tight to isoclinal folding of the Gorge Creek Group and metamorphism of adjacent parts of the Whundo Group, prior to deposition of the Whim Creek Group. The depositional setting of the Whim Creek Group was interpreted as a pull-apart basin by Barley (1987), but Pike and Cas (2002) suggested it formed in an ensialic back-arc basin. Smith (2003) considered that the TTG of the contemporaneous Maitland River Supersuite (3.00–2.98 Ga)

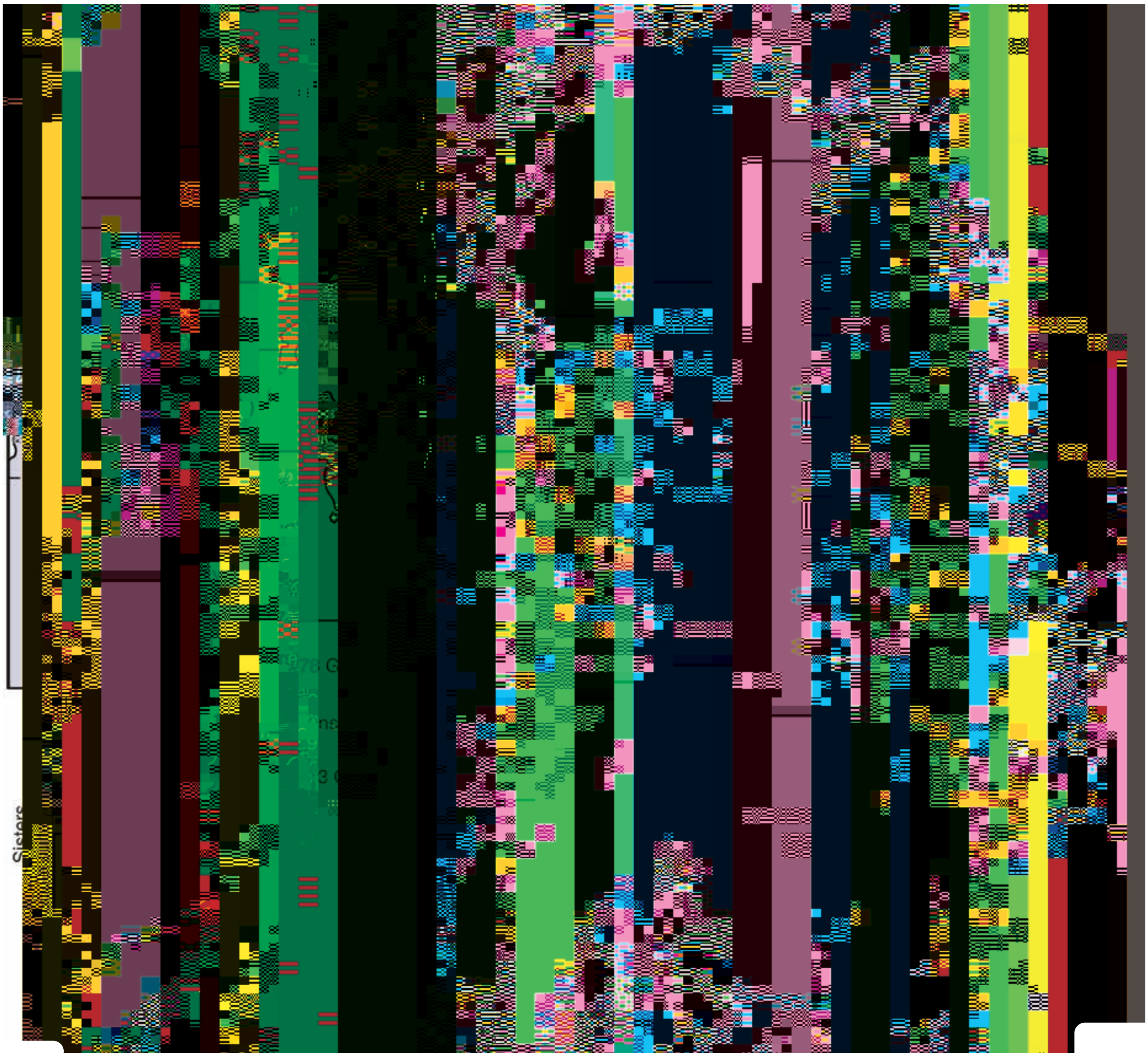

Figure 5 Simplified geology of the NW Pilbara Craton, showing stratigraphy and major structures. The three terranes (Karratha, Regal, and Sholl) are separated by major faults, and each has an entirely different stratigraphy and tectonic history.

represents the roots of a continental arc, and a subduction origin is supported by the geochemistry of basalt in the group, in particular its enrichment in Th and LREE, which is consistent with an enriched mantle source. However, such mantle enrichment is also present in magmas that later intruded the Mallina Basin, and these have not of the Fortescue Basin was accompanied by a marked thickening of the succession in the S, consistent with a major rift axis to the SSW. In the S Pilbara, the Tumbiana Formation of stage 3 is represented by the Pyradie Formation, a 1 km-thick marine unit of komatiite, komatiitic basalt, hyaloclastite, argillite, and chert. In the S Pilbara, the Jeerinah Formation is much thicker than in the N, and consists of 'deeper' shelf deposits, including basalt, as well as being extensively intruded by dolerite sills.

Hamersley Basin

The Hamersley Basin, which contains the BIF-dominated Hamersley Group (Trendall and Blockley, 1970), overlies most of the southern part of the Pilbara Craton, and its lower stratigraphy is also preserved close to the E and W margins of the craton (Figure 1). In the S and W, the basin stratigraphy represents continuation of the shelf subsidence in stage 4 of the Fortescue Basin, but in the E, deposition was in shallow water and there is no evidence that the central and upper parts of the Hamersley Group were ever deposited here, or across most of the N Pilbara. In the S Pilbara, the Hamersley Group is c. 2.5 km thick, lies conformably on rocks of the Fortescue Group, and includes four BIF-dominated formations (Marra Mamba,

Lower Wyloo Group

The lower part of the Wyloo Group consists of the basal Beasley River Quartzite (up to 360 m thick), which is conformably overlain by the Cheela Springs Basalt and the Wooly Dolomite (Figure 6). This succession lies with marked unconformity on rocks of the Turee Creek and Hamersley basins. The basal Three Corner Conglomerate Member of the Beasley River Quartzite contains abundant clasts of BIF, including pebbles of enriched ore derived from erosion of the Hamersley Group. The 2.21 Ga Cheela Springs Basalt is up to 2 km thick and consists of basalt derived from a subduction-modified source (Martin and Morris, 2010). The overlying 2.03 Ga Wooly Dolomite is a shallow-marine carbonate succession with locally abundant stromatolites. All of the rocks in the lower Wyloo Group are cut by dolerite dykes emplaced at 2.01 Ga.

Upper Wyloo Group

Deposition of the upper Wyloo Group at 1.83–1.79 Ga included early passive rift deposits, pre- to syn-collisional volcanics (arc?), and younger syn-collisional deposits culminating with the Capricorn Orogeny. The basal Mount McGrath Formation unconformably overlies folded lower Wyloo Group and older rocks, and is composed of upward-fining deltaic and shallow-marine cycles composed of channelized conglomerate and siltstone (Thorne and Seymour, 1991). The conformably overlying Duck Creek Dolomite is up to 1 km thick and consists of repeated upward-shallowing sequences formed by transgressive and regressive sedimentation on a barred carbonate shoreline (Grey and Thorne, 1985). The formation includes slope, barrier-bar, lagoon, intertidal and supratidal facies, together with major developments of subtidal stromatolitic bioherms. The Duck Creek Dolomite is conformably overlain by relatively deep-water sedimentary and volcanic rocks of the >5 km-thick, 1.83–1.795 Ga, Ashburton Formation.

Archean–Paleoproterozoic biosphere

Fossil occurrences in the Pilbara region are widespread and preserved in a variety of depositional environments (e.g., Buick and Dunlop, 1990; Brasier et al., 2002; Van Kranendonk, 2007; Hickman, 2012). Within the Pilbara Supergroup, stromatolites, microbial mats, and microfossils have been identified within thin sedimentary units that separate volcanic cycles. The most common habitat was hydrothermal, such as around hot springs or adjacent to hydrothermal vents in settings associated with the waning stages of volcanic activity; such environments were provided by the 3.48 Ga Dresser Formation (Walter et al., 1980; Buick and Dunlop, 1990; Philippot et al., 2007; Van Kranendonk et al., 2008) and the 3.24 Ga Kangaroo Caves Formation (Duck et al., 2007). However, in the case of the Strelley Pool Formation, the growth of stromatolites was prolific in a shallow-water carbonate shelf setting (Hofmann et al., 1999; Allwood et al., 2006). Evidence of Paleoarchean life may also lie in some of the BIF units of the succession because oxidising bacteria or photosynthesising microbiota could have caused BIF deposition through oxidation of dissolved Fe^{2+} (e.g., Trendall and Blockley, 1970, 2004). The oldest known BIF in the Pilbara Craton is present within the c. 3.52 Ga Coucal Formation.

The Early Mesoarchean successions have so far yielded relatively little evidence of early life. In the passive margin deposits of the E Pilbara, Duck et al. (2007) identified structures resembling microbial mats near the base of the Soanesville Group. In the W Pilbara, Kiyokawa et al. (2006) reported various structures suggestive of microbial mats and filamentous organic remains from 3.19 Ga oceanic crust at the top of the Regal Formation. In the shallow-water sedimentary rocks at the base of the Late Mesoarchean De Grey Superbasin, microstructures like threads, films, hollow spheres and spindles are interpreted as remnants of microfossils and microbial mats (Sugitani et al. (2009) and within the overlying Cleaverville Formation of the W Pilbara, carbonaceous spheroids occur in black chert (Ueno et al., 2006).

The Neoarchean Fortescue Basin contains widespread stromatolites in lacustrine carbonate units of the Kylena Formation and Tumbiana Formation (Sakurai et al., 2005; Awramik and Buchheim, 2009). Microbial structures within Tumbiana Formation stromatolites were described by Walter (1983) and Lepot et al. (2008). Stromatolites also occur in shallow-water chert at the base of the Jeerinah Formation (Packer and Walter, 1986). Water depths in most formations of the Hamersley Basin were too great for stromatolites, but the shallow-water Carawine Dolomite of the E Pilbara is an exception and is abundantly stromatolitic. The Wooly and Duck Creek Dolomites of the Wyloo Group also contain abundant stromatolites.

Archean–Paleoproterozoic atmosphere

It is generally accepted that there was a major increase in the O_2 content of Earth's atmosphere between 2.4–2.0 Ga (Farquhar et al., 2000), commonly referred to as the 'Great Oxidation Event' (GOE; Holland, 2002). However, some workers have argued either that the atmosphere was oxygenated as early as 4.0 Ga (Ohmoto et al., 2006), or that oxygen increased more gradually or fluctuated from the Paleoarchean to the Paleoproterozoic (e.g., Anbar et al., 2007).

Many workers have used sulfur isotopes to argue that atmospheric oxygen levels were very low prior to the GOE (e.g., Farquhar et al., 2000; Pavlov and Kasting, 2002), based on observations that Archean sedimentary rocks exhibit mass independent fractionation (MIF-S), whereas sedimentary rocks deposited after the GEO do not. Because MIF-S can originate through ultraviolet radiation of volcanic SO_2 [illegible] glaciation in the Pilbara is provided by the <2.45 but >2.21 Ga Meteorite Bore Member of the Turee Creek Group.

Archean–Paleoproterozoic mineralisation

Pilbara Craton

The recognition that the Pilbara Craton is composed of geologically distinct terranes and basins, formed in different tectonic environments, has explained the large variety of mineralisation styles across the craton. Huston et al. (2002b) reviewed mineralisation of the craton within the context of its crustal evolution. Mineralisation in the East Pilbara Terrane occurred during a sequence of magmatic pulses related to mantle plumes, and extended over almost 300 Myr. Deposit types associated with these events include: synvolcanic Cu-Zn-Pb-barite volcanic-hosted massive sulfide (VHMS) deposits; hydrothermal barite in the form of both quartz-barite veins and sediment-replacement bedded chert-barite deposits; polymetallic and base metal deposits in porphyritic felsic stocks; porphyry Cu-Mo mineralisation; and mesothermal Au deposits in shear zones around granitic domes. Several of the Paleoarchean ore deposits are the oldest of their type in the world: hydrothermal barite in the Dresser Formation (3.48 Ga); volcanic-hosted massive sulfides (Cu-Pb-Zn, with 20% barite) in the Duffer Formation (3.465 Ga); polymetallic (Cu-Pb-Zn-Au-Ag) mineralisation in a porphyritic felsic stock (3.45 Ga); porphyry Cu-Mo (3.31 Ga); epigenetic lode Au deposits as old as 3.40 Ga (Huston et al., 2002b).

The c. 3.2 Ga rift-related passive margin successions contain little known mineralisation other than Au in the Nickel River Formation. The Au has been mined from shear zones within the Regal Thrust Zone, and it is uncertain if the source of the Au is detrital or hydrothermal. Rift-related ultramafic-mafic intrusions of the Dalton Suite (3.18 Ga) contain Ni-Cu mineralisation, but grades are generally <1% Ni. The Regal Terrane (oceanic crust) is apparently unmineralised, but the Whundo Group of the Sholl Terrane (3.13–3.11 Ga volcanic arc succession) locally contains economic VHMS Cu-Zn mineralisation.

The De Grey Superbasin contains the most economically important mineralisation in the Pilbara Craton. Iron ore from various deposits within the Gorge Creek Basin (3.05–3.02 Ga) has been mined and exported for almost 50 years. The Croydon Group contains c. .2.95 Ga VHMS and sediment-hosted Pb-Zn and Cu deposits at several localities. These deposits were formed during the early stages of alternating extension and compression in the basin, as were Ni-Cu and V-Ti-magnetite deposits in ultramafic-mafic layered intrusions intruded into the basin between 2.95–2.92 Ga. Orogenic vein- and shear-hosted Au deposits were formed during closure of the Mallina Basin at about 2.92 Ga (North Pilbara Orogeny). In the SE Pilbara Craton, the Mosquito Creek Orogeny was accompanied by similar orogenic Au deposits between 2.93–2.90 Ga.

The final period of mineralisation in the Pilbara Craton occurred between 2.89–2.83 Ga with pegmatite-hosted Sn-Ta deposits around the margins of highly fractionated post-orogenic granites of the Split Rock Supersuite. Shear-hosted Au mineralisation occurred at 2.89 Ga in the Mount York area (NW part of the East Pilbara Terrane).

Fortescue, Hamersley, and Turee Creek basins

The basal unconformity of Fortescue Basin is locally overlain by conglomerate-hosted Au mineralisation in areas where Neoarchean paleodrainage systems were eroding lode Au deposits in the underlying Pilbara Craton. An important lode Au deposit, Paulsens, has recently been developed in the lower Fortescue Group of the Wyloo Dome (SW Pilbara). Underground mining has reached a depth of 400 m, and current production is approximately 75,000 oz Au per annum. In the NE Pilbara, hydrothermal quartz veins have locally been mined for Pb, Ag, fluorite, Cu and V. BIFs of the Hamersley Basin, notably the Brockman and Marra Mamba iron formations, contain some of the world's largest deposits of Fe ore, owing to enrichment that has locally increased grades to approximately 60% Fe (Blockley, 1990).

Ashburton Basin

Since the review of mineralisation in the Ashburton Basin by Thorne and Seymour (1991), significant Au deposits have been mined from quartz veins in the Ashburton Formation. Sener et al. (2005) dated the Mount Olympus deposit at 1.74 Ga, and interpreted it to represent orogenic Au mineralisation. Syngenetic stratiform Au-Ag mineralisation in the Ashburton Formation has been interpreted to represent submarine hot-spring deposits (Davy et al., 1991). Other mineralisation in the Ashburton Basin includes Cu, Pb, Zn and Ag along fault zones.

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