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Invited Review Article

Gold production and the importance of exploration success: Yilgarn Craton, Western Australia

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ABSTRACT

The Yilgarn Craton has emerged as one of the world's premier gold-producing areas and the site of some exceptional exploration successes since 1980. The Yilgarn Craton overtook the iconic Witwatersrand goldfields of South Africa in 2013 based on their annual gold productions. This revolution in Yilgarn production and discovery is not typical of other parts of the world. Furthermore, the success is not adequately explained by gold price, mining equipment or processing—these are all useful, but they are global factors shared by all nations. Critical to becoming a leading gold producer has been the sustained exploration success in the Yilgarn Craton that has led to a pre-eminent Resource base. By not considering a global view, the magnitude and the importance of greenfields and subsequent brownfields exploration success has been under-estimated in summaries analyzing the Australian and Yilgarn gold industry.

It is contended that the correlation between exploration success and gold production is fundamental, and that exploration success is a prime way to differentiate the fortunes of various gold regions going forward. The popular explanation that Australian production rose because the global price increased lacks basic support. Put simply, high gold price and great technologies count for little if there is no resource to mine.

1. Introduction

Just as there are lessons to be learned from failure, there are also valuable lessons derived from success. In the case of mineral production, one lesson is to understand what facilitated previous success in order that such success can be repeated subsequently in the same terrane or in another constituency.

The Yilgarn Craton of Western Australia has been the site of a tenfold increase in gold production from 1979 that has been sustained for three decades (Fig. 1). That production comes from over 100 open pit and underground mines throughout this large cratonic terrane of Archean granite and greenstone belts (Fig. 2; Blewett, 2012; Vearncombe and Elias, 2017). The Yilgarn had a history of significant gold production since the 1880s, but by the 1960–70s, nearly all the Yilgarn gold mines had closed, and there was no public suggestion nor political commitment to reverse its 70-year production downtrend. The focus of this study is the discovery of new Yilgarn goldfields that have generated the 1980s turnaround. The production history of the Yilgarn Craton, and that of individual countries including Australia, are provided, followed by a summary of the results of exploration for the period following 1979. In this paper, gold price, mining technologies and processing advances are investigated as alternative possible causes to successful exploration in terms of this production increase.

A companion paper considers the geological factors contributing to exploration success in the Yilgarn Craton, including exploration methods and new exploration concepts. In that paper, three geoscientific breakthroughs related to primary gold deposits, and three related to gold exploration in the regolith, are identified as critical factors. Although discovery and production figures are extended to 2017, this study is focused on the period up to 2000; the reason for this is to give the benefit of time to consider influential factors of a longer-term nature beyond annual political and economic movements. The period from 2000 onwards is one of sustained production (e.g. Vearncombe and Phillips, in prep.), but unlike the period of 1979–2000 which involved most of the growth in production.

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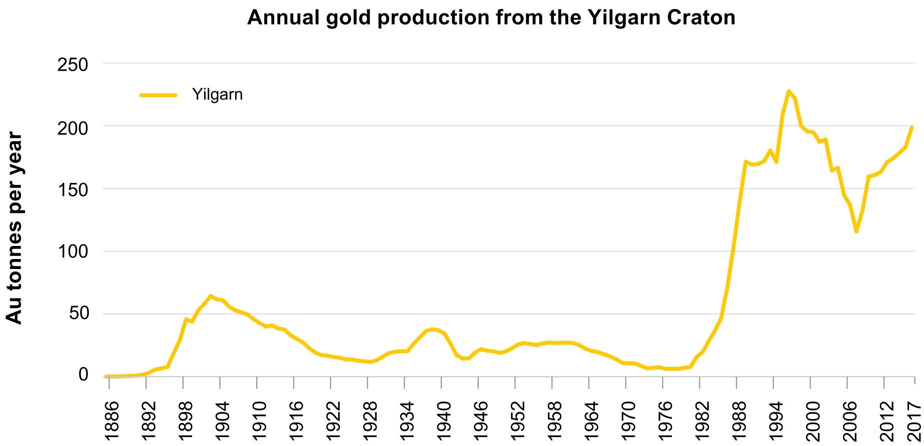

Fig. 1. Annual gold production from the Yilgarn Craton, Western Australia to the end of 2017. This demonstrates rapid growth from the 1980s and then sustained high production. Gold production from the Yilgarn has been calculated by using the published figures for Western Australia and then removing the contribution coming from the major Telfer gold deposit (see *Yilgarn figures* in the Appendix; One hundred tonnes is approximately three million ounces).

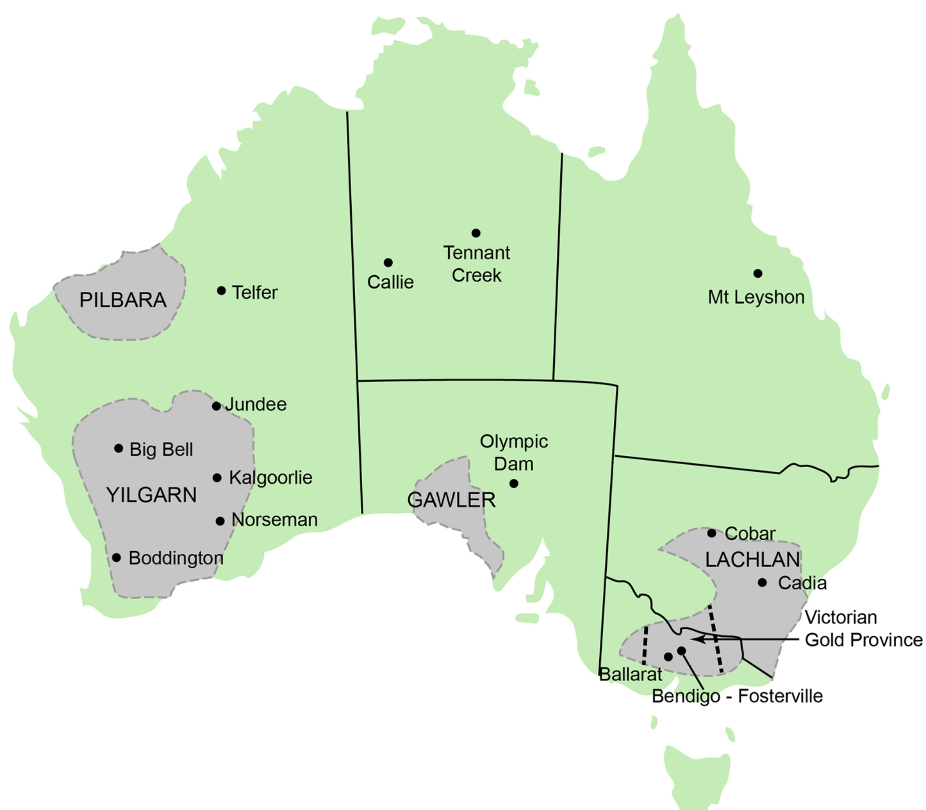

Fig. 2. Map of Australia showing Yilgarn Craton, Gawler and Pilbara cratons, Lachlan Orogen, the Victorian gold province, and several goldfields named in the text.

2. Gold production from 1950 to 2017

Many measures can track activity within a gold industry, and here the focus is primarily on production. Individual businesses may perceive the commercial conditions, as affecting them, somewhat differently if their measure of activity is meters drilled, funds raised, new companies listed, share price, infrastructure in progress, employment, or volume of mining supplies. The benefit of using production is that this measure is unequivocal, independently assessed, and ultimately one of the prime reasons that many of the industry support-activities exist and are commercial. For this discussion, gold production from the Yilgarn Craton is separated into pre- and post-1979/80, with the change-over being the start of 1980 and the dramatic 20th century peak in gold price.

2.1. Yilgarn gold production from 1950 to 1979

If Yilgarn gold production was monitored from 1950 until 1979, it would be easy to conclude that here was a sunset industry. Two thousand small and several mid-scale operations had run out of ore and closed. From a peak of Yilgarn production in 1903 of just over 60 t Au, when Australia led world gold production, figures for the Yilgarn Craton, and for Australia overall, had been in decline consistently except for a small upturn related to the Second World War (Fig. 1; Phillips, 2017 figure 1). Yilgarn production in the mid-20th Century relied upon discoveries made between 1892 and 1910.

Yilgarn gold production during the 1950–60s was 20–30 t (up to 1 Moz) per annum, and then fell from the late 1960s to around 10 t per annum. The larger producers at the time included the Kalgoorlie and Norseman goldfields, and these two had only small resource bases.

In 1979, Yilgarn exploration priorities were copper, uranium and nickel, and the area was hardly considered a new frontier. If someone was to propose an innovative exploration program for Yilgarn gold, it may have been rejected with a simple statement that Yilgarn gold was *mature*. It should be noted that the usage here of *mature* is not one the authors recommend. It mimics a common usage where someone or some group wishes to kill a project. When terminology is used in this way to degrade initiatives, there is likely to be no scientific basis for the statement. Here, the history of Yilgarn gold since 1979 illustrates the lack of any reasonable basis for calling this exploration area *mature*. Gold exploration did not become a priority in the Yilgarn until the early 1980s.

2.2. Yilgarn gold production from 1980 to 2000

In 1980 and 1981, Yilgarn annual gold production of 7 tpa (tonnes per annum) was almost as low as it had ever been since the first discovery of gold a century before. After 1980, Yilgarn gold production rose modestly at first and then quite sharply to 170 tpa by 1990 (Fig. 1). This rise involved a doubling of production in 1982, doubling again by 1984, yet doubling again by 1987, and again by 1989. Annual production then rose a further 50 percent by 1996 to 220 tpa gold. For the whole 1980–2000 period, significant year-on-year production decreases were rare. Since the 1980s, the Yilgarn gold industry, including Perth-based mining suppliers and exploration and mining software developers, have been responsible for many global technological advances in gold mining. By 2013, the Yilgarn Craton was producing more gold each year than the iconic Witwatersrand goldfields of South Africa.

Up to 1980, virtually all the gold from the Yilgarn Craton came from gold-only deposits from which base metals were not recovered. After 1980, gold-only deposits were still dominant and there were many more of them (Fig. 3); the main *gold-plus* deposit was the Golden Grove deposit that produces Cu-Au in the west of the Yilgarn Craton. Much of the gold production in the 1980s came from near-surface oxidized ores and open pit mining, but in the 1990s more primary ores were being exploited by underground mining.

It is significant that the pattern of Yilgarn production was not paralleled in other gold producing regions of Australia shown in Fig. 2. Amongst Australian Archean terranes, gold production is highly skewed towards the Yilgarn Craton, with only minor production from the Gawler and Pilbara Cratons. The largest all-time gold producing part of Australia, as of 1979, was the Victorian gold province, but its relevance after 1980 was an order of magnitude less than that of Western Australia and the Yilgarn Craton.

2.3. Global gold production from 1950 through 2000

Global gold production during the 1950–2000 period is slightly complicated by uncertain figures from the USSR and then Russia, and the omission of accurate Chinese production. Some pre-1986 figures really reflect Western World production, and so although gold production from USSR, Russia or China is not analysed here, these countries are recognized as very important gold producers.

Global production rose slowly during the 1950s and 1960s, then steadily from 800 tpa gold to 1500 tpa by 1970. Through the 1970s, global production fell slightly, but the 1980s were a period of significant global increase to over 2000 tpa gold. From 1990 to 2000, and even to 2010, global gold production remained constant (2000–2500 tpa) and has risen since 2010 to 3000 tpa.

Gold production from the USA followed a very similar path to Australia with minor production before 1980, a tenfold increase during the 1980s, and then sustained production at the new level (Fig. 4). Much of the increase came from Nevada and involved mining of the Carlin-type gold deposits discovered in 1961 (Bettles, 2002). Canada, with a gold industry predominantly based upon its Archean Superior Craton, followed a different production path from the Yilgarn Craton. Canada also saw a rise during the 1980s, but from producing three times as much gold as Australia in 1980, it was producing only one half of Australian production by 2000. Brazilian production (not shown) is also dominated by goldfields in Archean rocks, and followed the production pattern of Canada, rising modestly in the 1980s, but falling slightly in the 1990s.

There are other gold producing countries that have followed the increasing production profile of USA and Australia, but with their rise of production occurring later and not reaching the same levels (Phillips, 2011). Examples include Indonesia, South Korea, Papua New Guinea (all rising around 1990), Argentina, Chile, Ghana, Mali, Mexico, Peru, Tanzania (all rising in the mid to late 1990s), and China rising to greater levels and starting in the late 1990s. Some other countries, such as the Philippines, have hardly changed their annual production in the period.

South Africa has been the major influence on global gold production through much of the 20th Century. By 1970, South Africa was accounting for two-thirds of (Western) World production from many large Witwatersrand mines based particularly upon the discoveries of the Carletonville (mid 1930s) and Welkom (1940s) goldfields. However, since 1970, South African production has fallen almost every year (Fig. 4) due to the lack of exploration success, decreasing gold grade, increasing tonnage and lower profitability, and at different times, accidents, strikes and parts of mines being merged or closed (Phillips, 2013).

2.4. Yilgarn and global gold production since 2000

A summary of gold production since 2000 is provided for completeness even though the focus is on understanding the successes of the 1980–2000 period in the Yilgarn goldfields. Global gold production was constant from 2000 to 2010 around 2500 tpa, then has risen to 3000 tpa in recent years. Of the major gold producing countries, production remains high in Australia and USA, and has been increasing in China, Russia and Canada, but continually falling in South Africa.

Several other countries have increased their gold resource base in the last two decades especially in West and Central Africa (e.g. Burkina Faso, Tanzania, Mali), parts of Asia (e.g. Indonesia, Papua New Guinea), South America (e.g. Columbia) and the Middle East. However not all have translated their exploration successes to significant production increases yet.

Yilgarn gold production has been consistently strong during this period from 2010, at around 160 tpa. Small decreases have coincided with closures (temporary in the case of the large Boddington mine), and increases have reflected new mines coming on-stream after discovery (Tropicana, Gruyere) and expansions of existing operations. The high level of annual gold production from the Yilgarn Craton from 2000 demonstrates the importance of the discoveries of the 1980s complemented by on-going exploration success to replace production (Phillips and Vearncombe, 2013; see also Section 3.1).

2.5. Yilgarn gold production growth in a global context

The most important aspect of the gold production figures discussed above is that countries have responded very differently to global conditions and the widely available technologies during the late 20th Century. In its growth after 1979, gold production from the Yilgarn goldfields, along with Nevada, has outperformed all other parts of the world during the 1980s (Fig. 4).

The purpose of this study is to investigate some factors that might have contributed to the Yilgarn outperforming other areas in terms of increased gold production. First, exploration for gold during this period is summarized, prior to examination of some commonly cited reasons for the increased production. Gold price is one of three reasons used to explain the Australian gold boom after 1979: the other two are the methods of mining, such as the availability of larger machinery, and new processing technologies, including carbon-in-pulp/leach (Close, 2002; Blewett, 2012). Mining and processing are examined only briefly as these are advances that have been available to all gold companies and most jurisdictions globally.

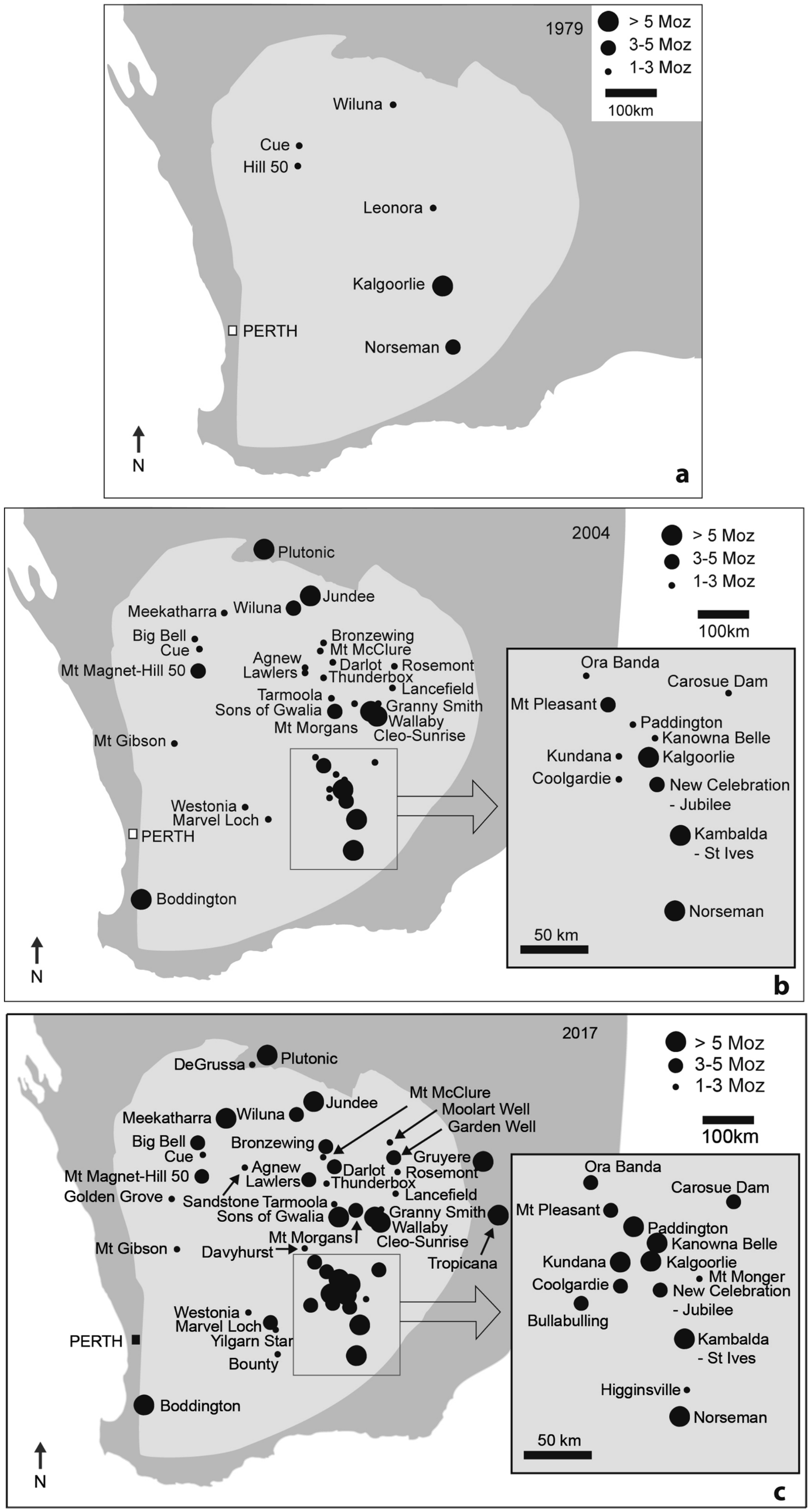

Fig. 3. 1979-top – Significant gold producers known in the Yilgarn Craton in 1979. All of these goldfields were closed in 1979 except for Kalgoorlie and Norseman. 2004-centre – Significant gold producers known in the Yilgarn Craton in 2004; most of the shown goldfields were actively producing at this time. 2017-bottom – Some significant gold producers known in the Yilgarn Craton in 2017 (Phillips, 2017).

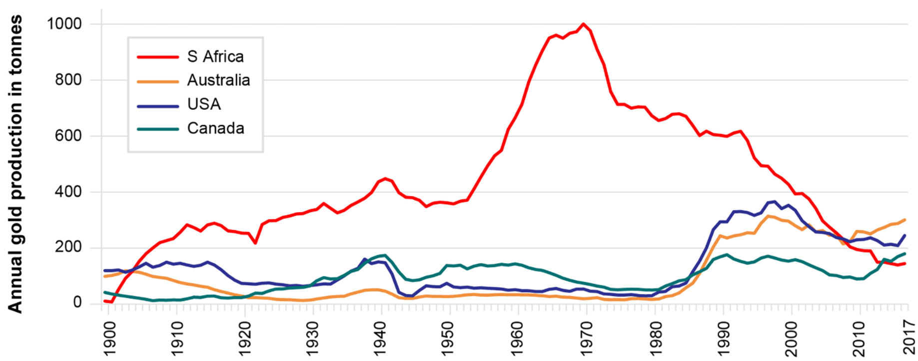

Fig. 4. Annual production from major gold-producing countries. The performance of Australia and USA (which is dominantly coming from Nevada) is very different to that of South Africa. The source of these figures is documented in the Appendix and they come directly or indirectly from the respective government and other official sources, e.g. Chamber of Mines in South Africa.

3. Measure of gold exploration success

Exploration success can be measured by combining Economic Demonstrated Resources (EDR) with production figures (Geoscience Australia, 2013; also see Appendix for definitions of terms). Discovery during a time interval is the sum of production during that period plus the increase in EDR. The approach can be applied both to assess the success of exploration in a province, and for comparison between countries. It is noted that using this method to calculate discovery can give anomalous answers if unreliable EDR figures are used, e.g. South Africa appears to have had substantial negative discovery using some of their government's previous EDR figures.

3.1. Gold discovery in the Yilgarn goldfields from 1980

At the start of 1979, Australian EDR was 220 t gold of which ~90 t is estimated to be attributable to the Yilgarn goldfields (i.e. by subtracting a contribution of 47 t for Telfer from the 135 t figure for Western Australia). In the period of 1979–1992, 990 t gold was produced from the Yilgarn Craton, and the Yilgarn EDR rose from 90 t to around 1500 t gold. This equates to 2400 t gold discovered in the Yilgarn Craton during the 1979–1992 period. To put this 2400 t gold into perspective, it was 2 percent of all the gold mined globally in 6000 years. Thus, the period immediately after 1980 was one of major exploration success for gold in the Yilgarn Craton: success that was not being paralleled globally.

The Yilgarn exploration success did not finish in 1992 but continued at an increasing pace for two more decades. Exploration success allowed Yilgarn gold production to continue at a high level while the resource base kept growing. There is a strong correlation between exploration success measured by growing EDR, and production (Fig. 5). Furthermore, these parameters provide a logical succession of conditions starting with the global price of gold rising from 1971 and remaining above the miserly level of the 1960s, exploration funds being raised for gold, exploration success with growth of EDR, new mine developments, successful early production, and profits being re-invested in exploration (Fig. 5).

In 25 years to 2004, cumulative Yilgarn production was 3116 tonnes gold, and EDR rose from 90 t to 2433 t gold: that is, nearly 6000 t gold were discovered in the Yilgarn in 25 years (Phillips, 2004; Fig. 5 – other figs.). Interestingly, discovery measured as tonnes per year increased in the decade after 2004, and cost of discovery per ounce decreased (Phillips and Vearncombe, 2013). To put the Yilgarn success into context, this discovery performance has not been bettered in the history of gold, except twice by South Africa in the 1880–90 and again in the 1930–40s.

Importantly, not all additions to EDR and production have been related directly to new greenfield discoveries (Brown and Vearncombe, 2014; Vearncombe and Phillips, in prep.). Kalgoorlie added over 500 t Au almost a century after its discovery by adopting a new approach to mining. The conversion of the Golden Mile in Kalgoorlie from a virtually closed 1000 t gold past producer around 1979, to a 15 tpa (i.e. 0.5 Moz) gold producer for the next two decades involved innovative thinking, active public championing of the concept of an amalgamated large open pit (the Kalgoorlie Superpit), and the necessary commercial moves to consolidate many small holdings (notably by Bond International Gold and its leader Alan Bond of America's Cup yachting fame). In the 2000s, a different type of innovative thinking was required to turn the closed Sons of Gwalia mine at Leonora (with over 100 t gold past production) into a significant current producer involving deep underground mining.

Whilst new greenfield discoveries may have become less common by some measures, this is partly due to the enormous success of past exploration and commercial logic of exploring near known mineralization and deposits. There are few greenstone belts in the Yilgarn that do not have significant deposits that have been mined (Fig. 6).

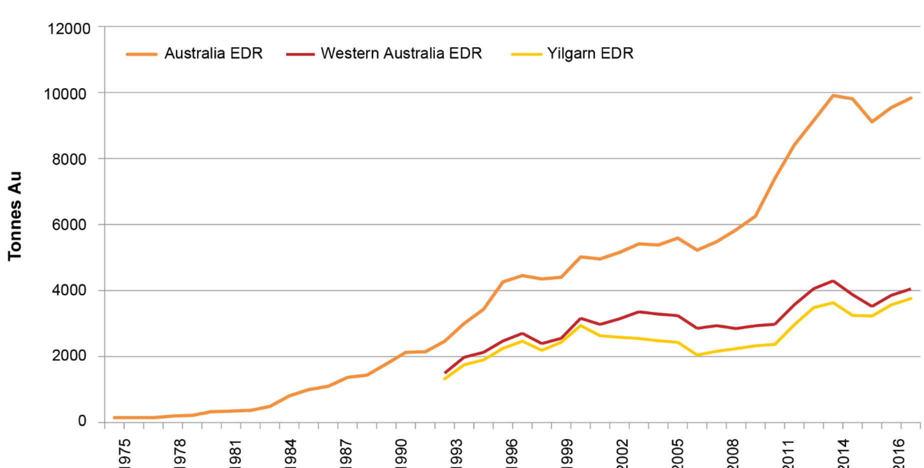

Fig. 5. Economic Demonstrated Resources of gold for Australia and the Yilgarn Craton for each year from 1979. Despite high levels of gold production, EDR, as measured at the end of each year, has continued to grow. The EDR attributable to the Yilgarn Craton has declined as a national percentage with the recent importance of Olympic Dam, Telfer and Cadia deposits in post-Archean rocks. A fall around 2014 reflects a revision of EDR for the very large Olympic Dam deposit in which gold is subordinate to copper production. EDR figures for Australia are published by Geoscience Australia, and the figures for the Yilgarn are calculated by removing the EDR figure for the Telfer gold deposit; the process is explained in the Appendix and the results tabulated there.

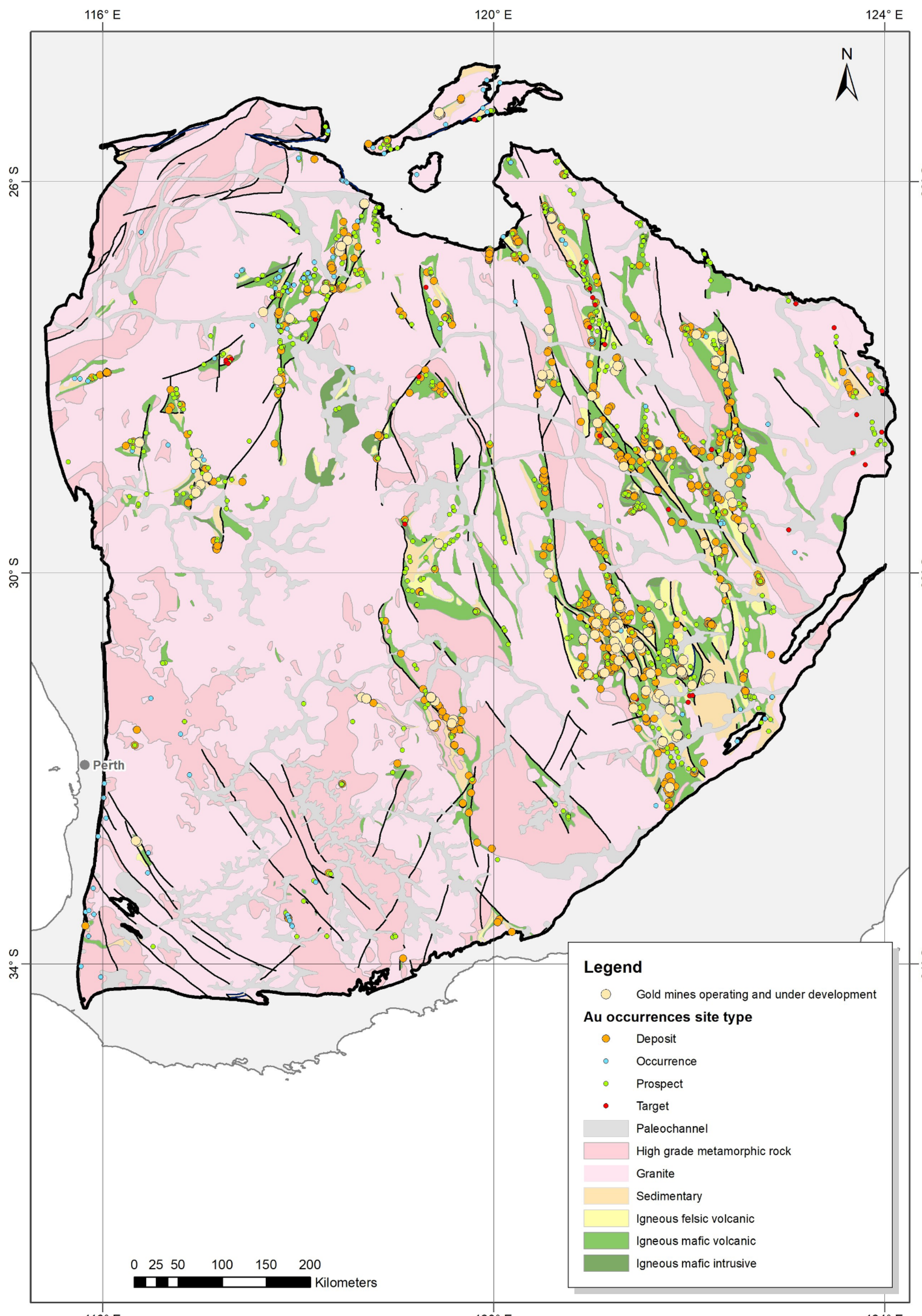

Fig. 6. Geology map of the Yilgarn Craton based on data from the Geological Survey of Western Australia showing the high-grade metamorphic rocks, greenstone belts and granite, the discontinuous shear zones on the granite-greenstone margins and gold deposits. .
Reproduced from Vearncombe and Elias (2017)

Most, but not all, of the Yilgarn greenstone belts are within trucking distance of an existing gold operation. The resource additions that have maintained the upwards trajectory of Economic Demonstrated Resources are mostly brownfields in nature. To this end, important characteristics of modern exploration that appear to be important include:

- the daily interrelationship between exploration staff and mining personnel with exploration managed and controlled onsite,
- the development (much of it in Perth) and onsite application of software enabling geology, exploration and mine data to be viewed and analyzed interactively and in 3D,
- deep navigational-controlled drilling, and drilling from underground, and
- the strong commitment of companies to maintain a pipeline of resources that are progressively upgraded to reserves in anticipation of the coming years of production.

A different picture emerges from alternative analyses that include Yilgarn gold (McKeith et al., 2010; Schodde, 2011). Such analyses are focused on greenfields discoveries and have portrayed a rather negative view of the Yilgarn gold province. This approach has an over-reliance on greenfields discoveries and substantially under-estimates the importance of brownfields additions well after any discovery (Phillips and Vearncombe, 2013; Phillips, 2017). It appears unlikely that any algorithm can reliably model the post-greenfields growth of resources in different goldfields as they reflect very different resource growth histories. For example, Norseman has had many, but small, resource additions over its century of operation, and is very different from Kalgoorlie in growth trajectory. At Jundee, 600 km north of Kalgoorlie, the 1992–3 greenfields discovery was in the order of 60 t gold (Wright and Herbison, 1995) but the endowment of this goldfield has risen to 240 t gold with the addition of Nimary, plus the discoveries of Barton Deeps in 1996 (35 t gold, Phillips and Vearncombe, 2011), Westside in 2001 (30 t gold, Hall et al., 2003) and Gateway-Gringotts (Smith et al., 2017). For greenstone-hosted gold deposits, post-discovery growth is critical to ultimate mine life, but takes on different pathways in different goldfields and, in our opinion, defies simple prediction.

It is encouraging for any new entrants into gold exploration and mining that, when the turnaround did occur in the early 1980s, the leading Australian producers of the 1970s were challenged by new entrants into the industry: over time, previous Australian gold leaders of the 1970s, such as Peko Wallsend and Western Mining Corporation, disappeared from the corporate scene.

3.2. Discovery outside Australia from 1980

Part of the USA was also experiencing major exploration success with the discovery of the Carlin gold deposit in 1961 in north-central Nevada (Bettles, 2002). Major discoveries nearby at Goldstrike Deep Post and Miekle followed in 1987–1989. USA gold production rose from 30 t in 1979 to 330 t in 1992 primarily based upon the Carlin-type discoveries and their subsequent production.

Meanwhile the opposite was happening in South Africa where that industry found no new goldfields after 1951 and watched as its EDR plummeted from 36 000 tonnes in 1992 (a South African government figure) to a 2009 figure of 6000 t (from the US Geological Survey) or even 3000 t (Hartnady, 2009), and its production fell progressively from 1000 tpa in 1970 to under 200 tpa since 2010.

Australia, USA and South Africa demonstrate a very strong correlation between their exploration success and gold production trends (Table 1). Australia and USA (Nevada) demonstrate strong exploration success evidenced by increasing EDR, whereas South Africa reflects poor exploration success evidenced by falling EDR. The case for this direct correlation is strengthened further by Canada and Brazil, both with modest exploration successes and modest production growth. It is contended that the correlation between exploration success and gold production is fundamental, and that exploration success is a prime way to differentiate the fortunes of various gold regions going forward. In the Yilgarn, greenfields exploration success of the 1980s and 1990s has been followed with ongoing substantial brownfields success.

Table 1
Fifty-year gold production trends by country, and potential contributing factors (for 1960s onwards). Gold price, including its source, is discussed in Section 4 and the Appendix. Exploration success and production reflect our qualitative assessments based upon national Economic Demonstrated Resource figures and national production data as also outlined in the Appendix.

	Higher gold price	Exploration success	Production pattern
South Africa	yes	negligible	long term decline
Philippines	yes	minor	steady
Brazil	yes	minor	small increase
Canada	yes	modest	increase
USA	yes	MAJOR	LARGE INCREASE
Australia	yes	MAJOR	LARGE INCREASE
within Australia			
… Yilgarn	yes	MAJOR	LARGE INCREASE
… Victoria	yes	negligible	low

4. Role of gold price in Yilgarn gold production

It may be self-evident, but if the early-1970s gold prices prevailed today, commercial gold production would be very difficult if not impossible in most jurisdictions. As such, the uncoupling of the US dollar and gold in 1971 has had a profound and long-term influence on gold price globally. However, this uncoupling does not necessarily explain the success of one region compared to others.

4.1. Nominal price (price on the day, see Appendix for definitions of terms)

The *nominal* gold price was US$35 per ounce for most of the period 1950–1970, rising towards $800 in the late 1970s before reaching $850 in January 1980 (including an intraday peak of $900). The *nominal* gold price has generally been over US$1000 per ounce since 2010 and peaked above $1900 in 2011. None of these figures are directly comparable with one another because they do not account for the effects of inflation and different buying power of a dollar over time.

4.2. Real gold price (adjusted for inflation and comparable over time)

The *real* gold price is used throughout this study because it allows comparisons through time. This is a price that is inflation-adjusted, with the adjustment being made back to 2017 (though the choice of this date is not critical for any of these patterns especially in the current low inflation environment). In places, the real gold price is expressed in Australian dollars to reflect influences on Australian gold producers.

In the period of 1950–1970, the gold price in *real* (inflation-adjusted) Australian dollar terms fell steadily (Figs. 7 and 8), and at the end of 1970, it was at its nadir and under $215 per ounce. From 15th August 1971, the US terminated the convertibility of US dollars to gold, and in turn, this uncoupling brought down the Bretton Woods Agreement of 22 July 1944 that had led to the *nominal* price being set at US $35 per ounce. The price of gold after the 1971 uncoupling could move more freely to reflected market forces including demand, speculation and fear.

On 6th October 1973, Israel was attacked by its neighbors in the Yom Kippur war. This was followed by OPEC [Organization of the Petroleum Exporting Countries] imposing oil production cuts and an embargo that lasted from October 1973 to 17th March 1974. During

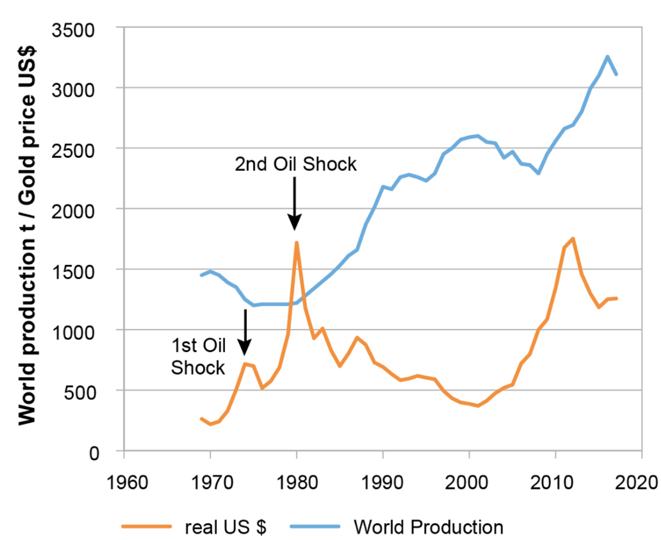

Fig. 7. Global gold production, and real gold price in US$. The global production figures prior to 1986 are for the Western World and do not include Communist countries, especially USSR, which was around 300 tpa gold. For the period of interest after 1970, price and production appear negatively correlated. The source of data is documented in the Appendix; prices are in 2017 USD.

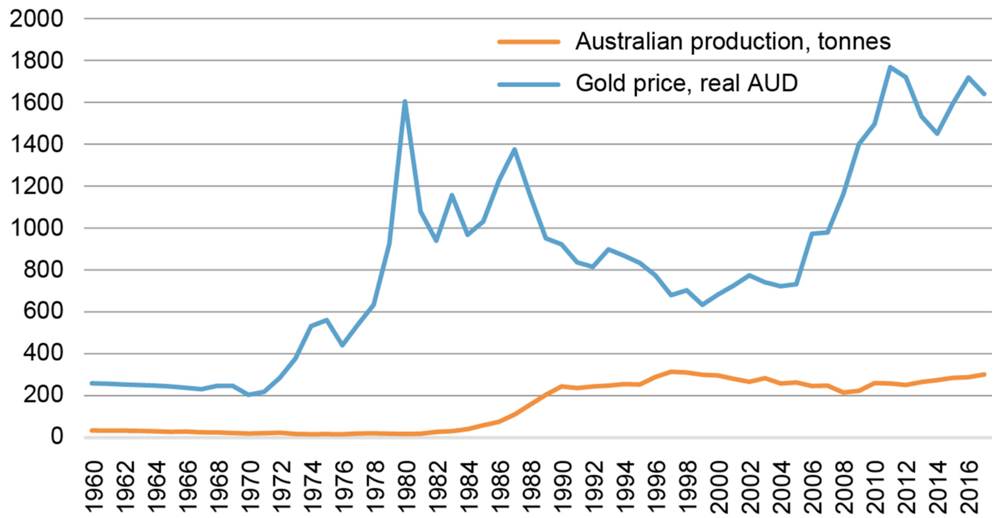

Fig. 8. Australian annual gold production, and real gold price in 2017 AUD$. Australian gold production rose between 1980 and 1990 and remained high. The production does not reflect changes in gold price. The source of data is documented in the Appendix.

this 'First Oil Shock', the oil price rose from $3 to $12 per barrel, and the gold price followed oil with a steep rise in 1974 from around $350 to $800 per ounce [real AUD$].

In the 'Second Oil Shock' starting in 1979, oil supplies from Iran were substantially reduced due to the Iranian revolution. A small reduction of OPEC production led to a substantial rise in the oil price, and, during the same period, the price of gold rose sharply to a real price of around $2000. On 27th December 1979, USSR invaded Afghanistan, leading to an intraday peak three weeks later.

Both the 'First' and 'Second Oil Shocks' involved rises of the gold price of 300–400 percent from the immediately preceding lows. Within one to two years of each of these peaks, the gold price had retreated substantially, though remaining above US$500 per ounce for almost the whole time until 1997.

4.3. Immediate effects of the gold price changes on gold production

Interestingly, the trebling of the gold price in the 'First Oil Shock' had virtually no effect on Australian gold production (see Fig. 8), except possibly saving the few existing mine(s) from closure. Similarly, there was minimal increase in revenue from gold sales by Australia because production was very low, being mainly from Telfer, Kalgoorlie, Norseman, and Tennant Creek (Fig. 3). Furthermore, Australia was in no position to bring operations into production quickly in 1973–4 because it had so few identified gold resources.

During the 'Second Oil Shock' of 1979–1980, there was no significant Australian gold production increase. Australia's annual gold production fell slightly during the 1970s (1970 = 19.3 t, 1980 = 17.0 t gold), and was 18.4 t gold in 1981, by which stage the 'Second Oil Shock' and gold price peak was essentially over. It was not until 1983 that Australia's gold production rose to the levels of the early 1960s and then continued to rise. Global gold production is hardly reflected during the 'Second Oil Shock' but rose in the late 1980s.

4.4. Statistical correlations of real gold price and gold production in the Yilgarn Craton

A plot of real gold price against Australian gold production shows subsets corresponding to pre-1980 low production and post-1990 elevated production (Fig. 9). There is no meaningful positive correlation between gold price and production in either subset, nor in the full data from 1949 to 2014.

A basic statistical analysis of annual gold price and Yilgarn production shows no strong correlation. For the years of 1970–2014, there is a weak positive correlation (0.30) and for the years specifically spanning the rise of production from 1980 to 1990 a moderate negative correlation (-0.52). There will almost certainly be algorithms that can link gold price and Yilgarn production (such as offsetting price by 10 years), but to be useful and meaningful such algorithms need to work for many more examples than Australia.

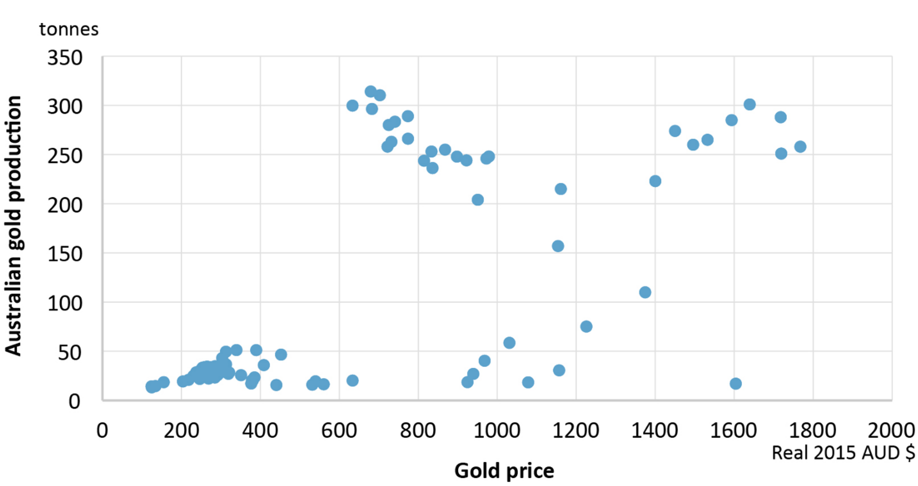

Fig. 9. Plot of the real gold price against Australian gold production for each year from 1928 to 2017. Each dot reflects a single year and the gold price for that year. The years after 1980 plot across the top as higher production years; the pre-1980 years are across the base. There is no meaningful correlation between gold price and production; instead, both high and low price can occur at the same time as high and low gold production.

4.5. Real gold price and its contribution to the outperformance of Yilgarn gold production since 1980

In summary, the popular explanation that Australian production rose because global price rose lacks basic support. For a set of countries, there are examples in which gold production has increased, decreased, and others in which it remained steady. Yilgarn annual gold production correlates poorly with annual gold price. Unquestionably, price plays a role in all gold production; but, as a globally shared factor, price does not explain the way in which Yilgarn gold production has outperformed other countries since 1980.

5. Role of mining equipment

Progressive improvements in mining equipment, including increases in scale, date back at least a century and include changes such as those prompted by large-scale mining of porphyry copper deposits in the early 1900s. It is not uncommon for there to be a perception at a single mine of step changes in mining technology: the effect here is real but reflects adoption by a mine site rather than contemporary innovation by industry. For example, this may arise when an individual operation continues for decades using less than state-of-the-art methods, and then, for whatever reason, upgrades their mining methods. This local perception of rapid change overshadows the more progressive and incremental nature of changes when viewed globally.

This can be illustrated by the Australian gold industry, which had been in decline for many years leading up to the 1950–70s and in which the mining methods of 1900 were still prevalent in goldfields like Kalgoorlie and Norseman in the late 1970s. Eventually the conditions were suitable for re-investment and many mining methods were introduced from elsewhere, and the larger trucks and faster ore movement led to lower mining costs. However, the reality was that Australian gold resources and production were very low before 1980, so it was too early to benefit much from these mining initiatives. The effect of larger-scale mining was to lower production costs and contribute to a shift to lower-grade open-pit mining using changes that were essentially available by the 1970s.

It is concluded that larger-scale mining was useful, but there is negligible evidence that mining equipment was a significant cause of relative increase of Yilgarn gold production in a global context.

6. Role of processing technologies including carbon-in-pulp and heap leach

As processing technologies improve through time, they offer cost savings at gold operations and potentially the ability to process otherwise uneconomic material. Two widely used processing approaches for gold ores are heap leaching, and carbon-in-pulp (CIP) and carbon-in-leach (CIL; Revuelta, 2018). Heap leaching of non-gold ores dates back hundreds of years and the use of the method for gold increased from the 1960s after its use at the Cortez gold mine, Nevada. Carbon-in-pulp processing was introduced to gold mining in Cripple Creek, Colorado in 1951, and later installed at Homestake mine, South Dakota in 1973 (Fast J L, written comm., 2015). Carbon-in-pulp processing was introduced to Australia in 1975 at Canbelego east of Cobar, Nullagine (Pilbara) and Evanston in the central Yilgarn (Close, 2002).

The minimal state of the Australian gold industry during the 1960s and 1970s, including the insignificant resources, meant that the uptake of heap leaching and carbon-in-pulp technologies in Australia was minor during these times. There is no evidence that either method had any large-scale effect on Australian gold production for years after each became available, i.e. prior to 1980.

Notwithstanding, heap-leaching and carbon-in-pulp technologies are quite applicable to gold ores in the Yilgarn Craton as evidenced by the wide application of these methods during the 1980s (Close, 2002; Hogan, 2004). The sequence of events suggests that these processing methods became valuable once new resources had been discovered. They are two of many existing technologies that were adopted to help reduce the costs of production. As gold mines shifted from dominantly open pit mining of supergene, weathered and oxidized ores in the 1980s to deeper hypogene ores in underground mines, CIP/CIL continued to play important roles in processing. The gold production of the Yilgarn Craton after 1980 appears not to be a direct function of access to any new mineral processing methods.

A parochial view, perhaps in Western Australia in the 1980s, would be to note a gold price spike along with some new mining and processing methods, and to immediately link these to explain the contemporary gold production increase. This view might even relate a price peak in 1980 with a production peak a decade later (Blewett, 2012, fig. B8.3), and though mathematically feasible, would not be consistent for other time intervals nor for other gold producing regions. A broader view would note that these factors are shared globally and mostly did not correlate with major gold production rises.

7. Discussion

Much can be learned by comparing and contrasting the fortunes of various gold provinces globally. Entrepreneurship and innovation, including technology uptake, have played important roles in Western Australia and Nevada, and the long-term stable fiscal and political regimes of both places have been important (Fraser Institute, 2017). Factors that appear exceptional during the rise of Yilgarn gold production are exploration successes built on scientific innovations and the willingness to uptake new ideas (Table 2; Hogan, 2004). Other factors might include a long-term industry commitment to discovery, geoscience excellence, well-trained geologists and quality exploration. At the same time as these scientific breakthroughs, there were important advances in geophysics, analytical processes and drilling.

Table 2
Scientific breakthroughs impacting upon Yilgarn gold exploration methods, and discovery (after Hogan, 2004).

Primary gold deposits	
Structural control (epigenetic timing)	Yilgarn gold deposits were not formed syngenetically on the seafloor; structures guided auriferous fluids and influenced orebody geometry
Favourable host rocks (mechanical and chemical properties)	Tensile strength and the concentration of iron and carbon was important in making some host rocks more auriferous than others
Alteration haloes (carbonate alteration related to gold deposition)	Carbonate and sulphide alteration were part of the gold formation event and hence could be used as exploration guides directly
Regolith-related breakthroughs	
Landforms and exploration tactics	Different landforms require different exploration methods giving rise to a RED scheme (residual, erosional, depositional) applied to the differing landscapes
Gold dispersion	Gold is mobile in some regolith environments and as it migrates laterally can create a broad exploration target at low concentration levels
Sampling media	Selective collection of Fe-rich surface material and calcrete may enhance gold levels particularly compared to the use of kaolinitic clays

Understanding the cause of the West Australian gold boom is important to Australian governments and industry, and to any other country considering its gold industry future. As examples, the government of South Africa has expressed intent to arrest that country's gold production decline of 1000 tpa to 150 tpa (30–5 Moz gold pa). Based upon this analysis, South Africa would be misguided to simply wait for a price rise. Instead, a positive initiative there would be to reverse its exploration record with new methods and especially new scientific ideas that can revitalize exploration success. Similarly, for Brazil to reach its aspiration of becoming a 180 tpa (6 Moz pa) gold producer, a sensible response would be to invest in exploration ideas rather than wait for a gold price rise. Meanwhile, Australia is well positioned with a strong gold industry, but costs need to be kept under control and there needs to be on-going exploration success. Investment in geoscience excellence to generate new exploration ideas and uptake of these ideas is crucial in the medium to long term.

8. Conclusion

Australia has enjoyed a major increase in gold production from 1980 that continues today. From producing 17 tonnes (0.5 Moz pa) of gold in 1979, production has averaged 250 tonnes or 8 Moz per annum since 1990. Two thirds of this gold production came from the goldfields of the Archean Yilgarn Craton in Western Australia. The Yilgarn Craton has been the site of a tenfold increase in gold production from 1979 that has been sustained for three decades. This steep increase in production from the Yilgarn Craton was not a universal global trend. There is a parallel with the Carlin gold province of Nevada USA, but countries such as Canada and Brazil, and regions such as the Victorian gold province, did not experience similar increases, and South African production decreased substantially after 1980.

Rising gold price, larger mining equipment and carbon-in-pulp (CIP) processing technology have been suggested as responsible for the increase of Yilgarn production. All were welcome and useful, but these were universal factors shared globally and do not explain any dis-proportionate regional success. Neither the 'First' nor 'Second Oil Shocks' of 1973 and 1979 provided lasting changes in the gold price that can be linked to the increase in Yilgarn gold production through the 1980s which, interestingly, coincided mostly with a falling gold price.

A strong correlation exists between gold production and discovery through successful exploration and innovation. There has been major exploration success in the Yilgarn goldfields from 1980, and this distinguishes the Yilgarn Craton (and Nevada) from most other regions around the world. New goldfields were discovered in the Yilgarn, and known goldfields were rejuvenated and enlarged dramatically. The result has been the discovery of over 8000 t gold (270 Moz) in the Yilgarn Craton since 1979. Putting this success into perspective, no region has ever had an equivalent period of gold discovery excepting South Africa immediately after 1886 and again around 1930–1940s. Exploration success in the Yilgarn utilized gold research and a diversity of new ideas and their active uptake especially by small to medium companies in Western Australia.

The suggested correlation of production and discovery is enhanced by the South African experience where unprecedented exploration successes in the 1930–40s preceded unprecedented production. Subsequently, the lack of discovery of any new goldfield since 1951 led to a four-decade fall in gold production that continues today.

Conflict of interest

The authors are not aware of any conflict of interest related to this work.

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Appendix

Production and price figures, currency conversions and inflation rates. Production figures are usually consistent amongst various sources, or nearly so (see Appendix table). They come directly or indirectly from the respective government and other official sources, e.g. Chamber of Mines in South Africa, and United States Geological Survey. The US price of gold is defined many ways and there is variability between sources; and we have used the National Mining Association (US) and Measuring Worth (https://www.measuringworth.com/datasets/gold/result.php) sources. Inflation rate and consumer price indices have multiple definitions, and are used to convert the historical US gold prices into Australian dollars. We have drawn upon Measuring Worth currency conversions through time, e.g. https://www.measuringworth.com/datasets/uscpi/result.php. Having been through this exercise several times, it has been preferable to retain US dollar gold prices wherever possible and acknowledge that prices received by Australian producers do change with currency fluctuations.

Yilgarn is an Aboriginal word for white quartz, and used here to refer to the Yilgarn Craton, and the goldfields contained therein. We avoid confusion by not following an older use of Yilgarn which referred to some hills north of Southern Cross, and subsequently that district.

Yilgarn figures. The Western Australian Mines Department does not collect statistics for the Yilgarn craton, *per se*; but collects statistics according to the slightly anachronistic *parish* system. However, for gold, figures for the Yilgarn Craton can be calculated using the published WA State figures which are dominantly a reflection of the Yilgarn plus the major Proterozoic Telfer goldfield. The latter was discovered in 1971, commenced production in 1977, has been one of Australia's largest gold producers for many years, has an all-time production exceeding 350 t, and has a total endowment of 600 t. A figure for Yilgarn gold production is attained by subtracting Telfer contributions from the figure for Western Australia. Apart from Telfer, no goldfield in WA outside the Yilgarn Craton has produced enough gold to significantly influence this calculation nor to alter the major conclusions presented here, i.e. all other non-Yilgarn goldfields are well under 100 t all-time gold production, in fact, under 30 t. These approximations appear valid given that Yilgarn gold endowment is about fifty times that of the Pilbara Craton (Table 3).

Table 3
(Appendix) Annual gold production for the world, Australia and Western Australia.

December of year	World	Australia		WA		Telfer		Archaean (i.e. ~ Yilgarn)	
	t	t	cum t	t	cum t	tpa	cum t	t	cum t
1851		10	10	0	0			0	0
1852		86	96	0	0			0	0
1853		93	190	0	0			0	0
1854		71	260	0	0			0	0
1855		87	348	0	0			0	0
1856		95	442	0	0			0	0
1857		88	530	0	0			0	0
1858		84	614	0	0			0	0
1859		78	692	0	0			0	0
1860		76	768	0	0			0	0
1861		73	841	0	0			0	0
1862		69	910	0	0			0	0
1863		63	973	0	0			0	0
1864		58	1030	0	0			0	0
1865		57	1087	0	0			0	0
1866		54	1141	0	0			0	0
1867		53	1194	0	0			0	0
1868		61	1255	0	0			0	0
1869		56	1312	0	0			0	0
1870		49	1360	0	0			0	0
1871		54	1414	0	0			0	0
1872		56	1470	0	0			0	0
1873		50	1520	0	0			0	0
1874		50	1570	0	0			0	0
1875		53	1623	0	0			0	0
1876		44	1667	0	0			0	0
1877		37	1704	0	0			0	0
1878		35	1738	0	0			0	0
1879		34	1773	0	0			0	0
1880		37	1809	0	0			0	0
1881		38	1847	0	0			0	0
1882		37	1884	0	0			0	0
1883		34	1918	0	0			0	0
1884		35	1953	0	0			0	0
1885		34	1987	0	0			0	0
1886		32	2019	0	0			0	0
1887		34	2053	0	0			0	0
1888		35	2088	0	0			0	0
1889		43	2131	0	1			0	1
1890		39	2169	1	1			1	1
1891		39	2208	1	2			1	2
1892		43	2251	2	4			2	4
1893		45	2296	3	7			3	7
1894		55	2351	6	13			6	13
1895		56	2407	6	19			6	19
1896		57	2465	8	27			8	27
1897		72	2537	19	46			19	46
1898		86	2623	29	75			29	75
1899		106	2729	46	121			46	121
1900	386	99	2828	44	165			44	165
1901	395	103	2931	53	218			53	218
1902	451	108	3040	58	276			58	276
1903	496	119	3159	64	340			64	340
1904	526	117	3276	62	402			62	402
1905	575	114	3390	61	463			61	463
1906	608	107	3497	56	518			56	518
1907	623	99	3596	53	571			53	571
1908	668	96	3691	51	622			51	622
1909	687	92	3784	50	672			50	672
1910	689	85	3868	46	718			46	718
1911	699	77	3946	43	760			43	760
1912	705	72	4018	40	800			40	800
1913	694	69	4087	41	841			41	841
1914	663	64	4150	38	880			38	880
1915	704	61	4211	38	917			38	917
1916	685	52	4263	33	950			33	950
1917	631	45	4308	30	980			30	980
1918	578	40	4348	27	1008			27	1008
1919	550	33	4381	23	1030			23	1030
1920	507	29	4410	19	1050			19	1050
1921	498	24	4434	17	1067			17	1067
1922	481	23	4457	17	1084			17	1084

(*continued on next page*)

Table 3 (*continued*)

December of year	World	Australia		WA		Telfer		Archaean (i.e. ~ Yilgarn)	
	t	t	cum t	t	cum t	tpa	cum t	t	cum t
1923	554	22	4480	16	1099			16	1099
1924	592	21	4501	15	1114			15	1114
1925	591	17	4518	14	1128			14	1128
1926	602	16	4534	14	1142			14	1142
1927	597	16	4550	13	1154			13	1154
1928	603	14	4564	12	1167			12	1167
1929	609	13	4577	12	1178			12	1178
1930	648	15	4592	13	1191			13	1191
1931	695	19	4611	16	1207			16	1207
1932	754	22	4633	19	1226			19	1226
1933	793	26	4659	20	1246			20	1246
1934	841	28	4686	20	1266			20	1266
1935	924	28	4714	20	1286			20	1286
1936	1030	37	4751	26	1313			26	1313
1937	1100	43	4794	31	1344			31	1344
1938	1170	50	4844	36	1380			36	1380
1939	1230	51	4895	38	1418			38	1418
1940	1310	51	4946	37	1455			37	1455
1941	1080	47	4993	35	1489			35	1489
1942	1120	36	5029	26	1516			26	1516
1943	896	23	5052	17	1533			17	1533
1944	813	20	5072	15	1547			15	1547
1945	762	20	5093	15	1562			15	1562
1946	860	26	5118	19	1581			19	1581
1947	900	29	5148	22	1603			22	1603
1948	932	28	5175	21	1624			21	1624
1949	964	28	5203	20	1644			20	1644
1950	879	27	5230	19	1663			19	1663
1951	883	28	5258	20	1683			20	1683
1952	868	30	5288	23	1706			23	1706
1953	864	33	5322	26	1731			26	1731
1954	965	35	5356	27	1758			27	1758
1955	947	33	5389	26	1784			26	1784
1956	978	32	5421	25	1809			25	1809
1957	1020	34	5455	26	1836			26	1836
1958	1050	34	5489	27	1863			27	1863
1959	1130	34	5523	27	1890			27	1890
1960	1190	34	5557	27	1917			27	1917
1961	1230	33	5590	27	1944			27	1944
1962	1290	33	5623	27	1971			27	1971
1963	1340	32	5655	25	1996			25	1996
1964	1390	30	5685	22	2018			22	2018
1965	1440	27	5712	20	2038			20	2038
1966	1450	29	5741	20	2058			20	2058
1967	1420	25	5766	18	2076			18	2076
1968	1440	24	5791	16	2092			16	2092
1969	1450	22	5812	14	2105			14	2105
1970	1480	19	5832	11	2116			11	2116
1971	1450	21	5853	11	2127			11	2127
1972	1390	23	5876	10	2138			10	2138
1973	1350	17	5893	9	2146			9	2146
1974	1250	16	5909	7	2153			7	2153
1975	1200	16	5925	7	2160			7	2160
1976	1210	16	5941	7	2167	0	0	7	2167
1977	1210	19	5960	11	2178	4	4	6	2174
1978	1210	20	5981	13	2191	7	12	6	2180
1979	1210	19	5999	12	2203	5	17	6	2186
1980	1220	17	6016	11	2214	4	21	7	2193
1981	1280	18	6034	12	2226	4	25	8	2201
1982	1340	27	6061	21	2247	5	30	16	2216
1983	1400	31	6092	24	2270	4	34	20	2236
1984	1460	40	6132	32	2303	4	38	28	2264
1985	1530	59	6191	41	2344	4	43	37	2301
1986	1610	75	6266	54	2398	7	50	46	2348
1987	1660	110	6376	78	2476	7	57	71	2418
1988	1870	157	6533	111	2586	8	66	102	2521
1989	2010	204	6737	147	2733	8	74	139	2659
1990	2180	244	6981	181	2914	9	83	171	2831
1991	2160	236	7217	179	3093	10	94	169	3000
1992	2260	244	7461	181	3275	12	106	169	3169
1993	2280	248	7709	183	3458	12	117	172	3341
1994	2260	255	7964	192	3651	12	129	180	3521
1995	2230	253	8217	190	3840	19	148	171	3692

(*continued on next page*)

Table 3 (*continued*)

December of year	World	Australia		WA		Telfer		Archaean (i.e. ~ Yilgarn)	
	t	t	cum t	t	cum t	tpa	cum t	t	cum t
1996	2290	289	8506	220	4061	11	159	209	3901
1997	2450	314	8820	238	4299	10	170	228	4129
1998	2500	310	9130	232	4531	10	180	222	4351
1999	2570	300	9430	211	4742	11	191	200	4551
2000	2590	296	9727	204	4945	8	199	195	4746
2001	2600	280	10,007	197	5142	2	201	195	4941
2002	2550	266	10,273	187	5329	0	201	187	5128
2003	2540	283	10,556	189	5518	0	201	189	5317
2004	2420	258	10,814	164	5682	0	201	164	5482
2005	2470	263	11,077	173	5856	7	208	166	5648
2006	2370	246	11,324	165	6021	20	228	145	5793
2007	2360	248	11,570	156	6177	20	247	136	5929
2008	2290	215	11,785	134	6311	18	266	116	6045
2009	2460	223	12,008	152	6463	20	285	132	6177
2010	2560	260	12,268	183	6644	21	307	160	6337
2011	2660	258	12,526	180	6824	19	326	161	6498
2012	2690	251	12,777	181	7004	17	343	163	6661
2013	2800	265	13,042	187	7191	16	359	171	6832
2014	2990	274	13,316	193	7384	17	366	174	7006
2015	3100	285	13,601	195	7579	16	382	178	7184
2016	3255	288	13,871	197	7776	14	396	183	7367
2017	3110	301	14,171	210	7987	12	408	198	7566

The Pilbara Craton accounts for less than 3% of the Archean endowment and is disregarded here.

All-time production is production since mining commenced at a location, and contrasts with annual production.

Carbon-in-pulp and Carbon-in-leach, or CIP/CIL, are methods for processing gold ores (Revuelta 2018).

Endowment reflects all-time production plus a reasonable assessment of current Resources. It is a particularly useful term in geological studies of deposits and goldfields. All-time production and endowment are not JORC terms nor are they officially sanctified.

Economic Demonstrated Resources is a term used by Geoscience Australia (www.ga.gov.au) and the US Geological Survey to provide a guide to reasonable national and global Resources. The best measure of Resources for a whole jurisdiction like WA or the Yilgarn Craton and covering half a century is Economic Demonstrated Resource (EDR) and we use this measure throughout this analysis. EDR for gold is a figure that comes from Geoscience Australia (GA) in their annual *Australia's Identified Mineral Resources* series, and in recent years, EDR for gold has been compiled by Alan Whitaker. According to GA, EDR today combines the JORC categories of 'Ore Reserves' and most of the 'Measured and Indicated Resources'; however, some of the earlier EDR figures used here pre-date the advent of JORC reporting. None of the numbers are perfect, nor are they independent of gold price and some assumptions; but they are very good.

The possibility that increasing Yilgarn production simply reflected price increase and a consequent upward recalculation of EDR (i.e. as sub-economic Resources became economic), was considered but was found to lack supporting evidence. If this had been the case, then EDR would rise immediately or at least when each annual reassessment of EDR was made. Instead, once established, production and EDR appear to be very resilient and do not reflect year-to-year price fluctuations. Furthermore, annual EDR is very resilient through the 25-year period and is not markedly recalculated upward and downward as price fluctuates: this does depend on assumptions being made in EDR calculations (i.e. by Geoscience Australia, 2013).

Greenfields and brownfields exploration: As inexact descriptors of exploration, *greenfields* and *brownfields* refer to the degree to which past exploration has been conducted on the tenements of interest. Greenfields exploration focusses on ground with minimal prior exploration, and the approach tends to be conceptual and using genetic and descriptive methods and regolith science. The target of greenfields exploration might be a new example of a known deposit, a new deposit type, or a whole new mineral province. Brownfields exploration is more descriptive in its approach and conducted close to known mineral deposits where it seeks extensions and repeats.

Gold price: there is not a single gold price even at one point in time: for example, a daily price could be opening, closing, average, high, low, or the twice daily London gold fix. Mostly an annual average is used here; some intraday highs have featured in the media.

Nominal price (of gold): this is the price exactly as quoted at the time. Because of the effects of inflation, $300 per ounce in one year may be very different in meaning to $300 per ounce decades earlier. Nominal price is rarely used here, and then just to convey the headline gold price of the day.

Real price (of gold) takes inflation into account and means that the prices for many different years can be sensibly compared. Real price is calculated by taking the nominal price and then adjusting it for inflation. Generally, we have used a real gold price expressed in a constant Australian dollar of March 2015 and then adjusted for 2017. Long term patterns do not alter if different dates are used.

Troy ounce is used for gold which is the conventional measure in the industry. One million troy ounces is the same as 31.1035 metric tonnes (the SI unit): this can be approximated as 1tonne = 30 K oz, and 1Moz = 30tonnes.

Tonnes per annum is abbreviated to tpa.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oregeorev.2018.12.011.

References

Bettles, K., 2002. Exploration and geology, 1962 to 2002, at the Goldstrike property, Carlin trend, Nevada. Soc. Econ. Geol. Spec. Publ. 9, 275–298.
Blewett, R.S. (Ed.), 2012. Shaping a nation: a geology of Australia. Geoscience Australia and ANU E Press, Canberra.
Brown, L., Vearncombe, J., 2014. Critical analysis of successful gold exploration methods. Applied Earth Science (Transactions) 123, 18–24.
Close, S.E., 2002. The Great Gold Renaissance: The Untold Story of the Modern Australian Gold Boom 1982–2002. Surbiton Associates, Melbourne, pp. 281.
Fraser Institute, 2018. Annual survey of mining companies 2017. Pp. 72.
Geoscience Australia, 2013. Australia's Identified Mineral Resources. Geoscience Australia, Canberra (produced annually, various issues have been utilised).
Hall, D., Maclean, D., Gebre Mariam, M., 2003. The discovery of the Westside gold deposit, Jundee – Nimary goldfield, Western Australia. In: New Generation Gold Mines: Case histories of discovery. Australian Mineral Foundation, Adelaide, pp. 18–33.
Hartnady, C.J.H., 2009. South Africa's gold production and reserves. South Afr. J. Sci. 105, 328–330.
Hogan, L., 2004. Research and development in exploration and mining: Implications for Australia's gold industry. ABARE eReport 04 (3), 35p.
McKeith, T.D., Schodde, R.C., Baltis, E.J., 2010. Gold discovery trends. SEG Newsletter April 2010, pages 1 and 18-24.
Phillips, G.N., 2004. Gold in the Yilgarn craton, Australia: a quarter century of successful exploration, and 100 Moz production. In: Muhling, J. (Ed.), SEG 2004: Predictive mineral discovery under cover; Extended Abstracts. Centre for Global Metallogeny, University of Western Australia, pp. 22–28.
Phillips, G.N., 2011. Gold exploration success: 33rd Sir Julius Wernher Memorial Lecture. Appl. Earth Sci. (Trans. Part B) 120, 7–20.
Phillips, G.N., 2013. Witwatersrand gold: discovery matters. Appl. Earth Sci. (Trans. B) 122, 122–127.
Phillips, G.N., 2017. Gold in Australia. The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 75–82.
Phillips, G.N., Vearncombe, J.R., 2011. Exploration of the Yandal gold province, Yilgarn Craton, Western Australia. Appl. Earth Sci. (Transactions Part B) 120, 44–59.
Phillips, G.N., Vearncombe, J.R., 2013. Australian gold exploration – following up the recent audit. AusIMM Bull. 76.
Revuelta, M.B., 2018. In: Mineral Resources. Springer International Publishing AG, pp. 653.
Schodde, R.C., 2011. Recent trends in gold discovery. New Gener. Gold Conf., Perth, abstract 1–19.
Smith, S., Haese, R., Grigson, M.W., 2017. Jundee gold deposit. The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 273–278.
Vearncombe, J.R., Elias, M., 2017. Yilgarn Craton ore deposits and metallogeny. The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 95–106.
Vearncombe, J.R., Phillips, G.N. in prep., The importance of brownfields gold exploration. Submitted to Mineralium Deposita, special issue on Orogenic Gold Deposits, 2019.
Wright, J.H., Herbison, I.D., 1995. The Yandal Belt – preliminary exploration of the Jundee deposit. In: New Generation Gold Mines: Case histories of discovery. Australian Mineral Foundation, Adelaide, pp. 5.1–5.13.