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Zircon Age Data from a Greenstone of the Archaean Yilgarn Block, Australia: Mid Proterozoic Heating or Uplift?

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Abstract. A new age determination has been made on the Greenstones of the Agnew-Jones Creek Area, Western Australia by use of the Zircon U-Pb dating procedure. Late stage granophyre from the differentiated Kathleen Valley doleritic sill provided zircons which are otherwise unobtainable from mafic rock suites. An upper intercept age of 2,795+38 Ma, extends the known length of the otherwise tightly established, late Archaean tectonic cycle at Agnew from 250 Ma to 320 Ma. A lower intercept of age 1,345±153 Ma is interpreted to record either a hitherto unknown very low temperature heating, or a hitherto unknown tectonic, uplift and cover removal, in the mid-Proterozoic. The existance of a postulated ancient unconformity of craton size dimensions may be being confirmed and dated. Apart from some inconclusive olivine and pyroxene Rb–Sr isotopic data from 190 km to the west, the only evidence known that could support either possibility is found outside the Yilgarn Block itself. Minor perturbations to a simple two-stage discordia pattern imply further small amounts of lead loss at later times. Studies of this nature could eventually provide information on the later history of stabilized cratons.

Introduction

Durney 1972, reported an Archaean conglomerate at Jones Creek, Western Australia, in a high-potential nickeliferous region, which resulted in a burst of geological investigation in the enclosing Sir Samuel sheet area of the Eastern Goldfields Province. One of these investigations was an extensive Rb–Sr geochronological study on the Agnew-Lawlers-Perserverance area (Fig. 1; Cooper et al. 1978), which was closely integrated to a concurrent detailed structural analysis (Platt et al. 1978), and greatly extended the high precision data reported earlier from the Mt. Keith Granodiorite area (Roddick et al. 1976; Fig. 1).

This dating effort was particularly successful in that a number of perfect fit isochrons (MSWD of 1 or less, McIntyre et al. 1966) were obtained that clearly defined separate emplacement times of four petrologically and chemically distinct types of magma, and of pegmatite formation associated with the latter two. The concurrent structural studies allowed the processes of volcanism, deformation, sedimentation and uplift to be fitted into an entirely consistent succession, for the first time unequivacally delineating a whole tectonic cycle at the 2,800–2,400 Ma age level.

The cycle is summarized in Table 3, together with new data from this work. The oldest rocks found are the greenstones which consist mainly of a complex of mafic and ultra-mafic volcanics and intrusives in the lower units, and involve sedimentary recycling in the upper part. Three periods of silicic intrusion, with decreasing volumes, have followed. The first is tonalite. The latter, leucogranite (adamellite) and leucotonalite, respectively, are both accompanied by pegmatites of the same age. Two intermediate folding events (Table 3) result in a north-south belt like exposure pattern of greenstones which run for several hundred kilometers.

A question left open in this study was the exact age of the oldest rocks exposed in the area. These greenstones are here metamorphosed to amphibolite facies (Durney 1972), and are believed to be the same continuous group over the mapped area of Fig. 1 (Durney 1972; Marston and Travers 1976). Greenstone material has proved most difficult to date isotopically because of the low Rb/Sr chemical ratios, gross chemical disturbance during post-formation, wet metamorphism, and the absence of zircon. At Kathleen Valley a gabbroic sill within the greenstones had differentiated to produce some more favourable granophyre material. The whole is now folded into the general sequence. SiO_2 contents range from 48% (gabbro) to 72% (granophyre) (Cooper et al. 1978). A Rb–Sr total-rock isochron on the sill material (Cooper et al. 1978) indicated that the greenstones were indeed the oldest rocks in the area, but the regression analysis revealed that, unlike the other rock types studied, the scatter of points obtained was far beyond that of experimental error. It was concluded that even here, in an originally comparatively dry igneous rock, the Rb–Sr total rock systematics had been disturbed by the subsequent amphibolite grade metamorphism, and a minimum age of greater than 2,718±50 Ma was the best possible estimate that could be obtained.

The age of the greenstone was the only uncertainty in the Archaean tectonic cycle unravelled at Agnew. Also, before 1981 no other greenstone in the whole Yilgarn Province had been dated accurately without making assumptions for the strontium isotope initial ratio (Turek 1966). It was therefore most desirable to attempt a zircon U–Pb

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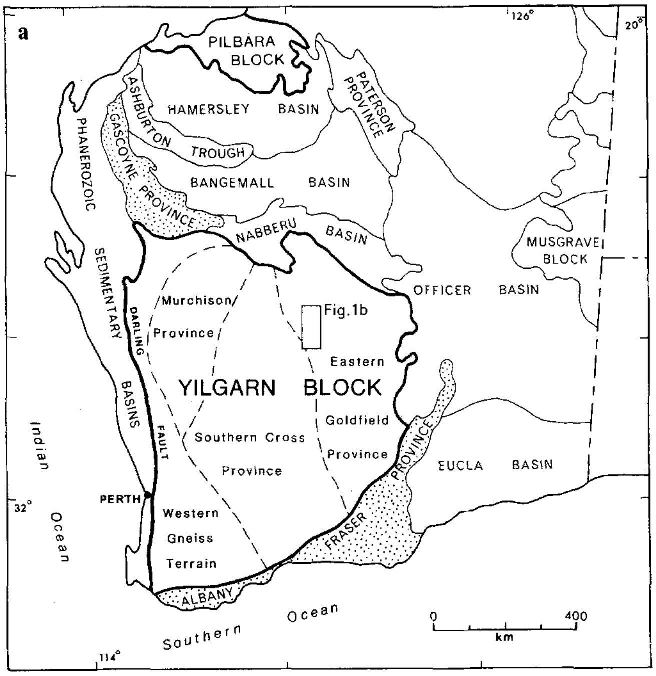

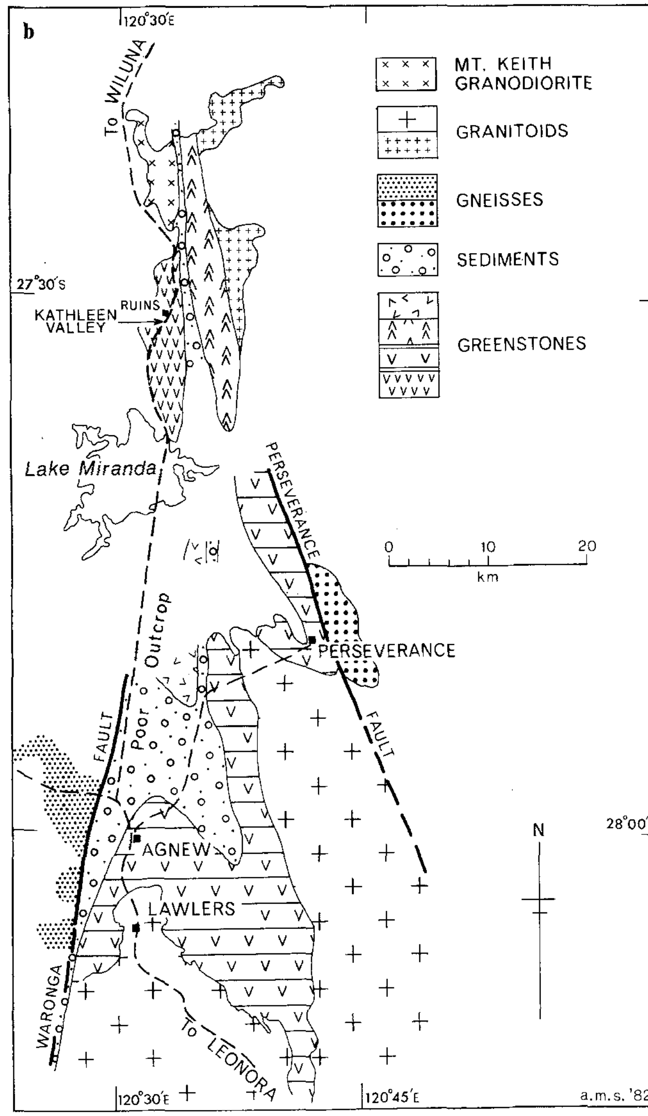

Fig. 1 a. Geographical location of the Yilgarn Block, Western Australia relative to its surrounding provinces and sedimentary basins **b.** Geological sketch map of the Agnew, Kathleen Valley, area of the Eastern Yilgarn Block, Western Australia (adapted from Cooper et al. 1976)

study in order to overcome this deficiency. Thin section examination, and an X.R.F. analysis of about 800 ppm zirconium on one of the samples, indicated that sufficient zircon mineral would be present to make such a study feasible.

Methods Used

All of the samples of the Kathleen Valley gabbroic sill used in the Rb–Sr study (Cooper et al. 1978) were taken from within 50 m of each other. Pieces of samples 75/19 to 75/33 which remained were combined to form a composite sample. This was crushed to −30 mesh size and zircon extracted using conventional Wilfley Table, heavy liquids and electromagnetic techniques. The zircon concentrate was divided first into size and then magnetic fractions. The grain colour ranges from honey-brown, through straw to pink in reflected, incandescent light. The more magnetic (high U content) fractions are frosty in reflected light and unevenly opaque in transmitted light. The less magnetic (low U) fractions are less opaque and have some clear transparent strips running through the opaque regions. A few prismatic faces have formed but most of the grains have sharp ragged edges. Some inclusions are present but no zircon overgrowths or older zircon cores could be found. The chemical analyses procedures for U and Pb content and Pb isotopic ratios were adapted from those of Krogh (8) (Krogh 1973). A mixed $^{208}Pb/^{235}U$ spike was used. Blank levels were 2 nanogramms of Pb of modern isotopic composition and 0.01 nanograms of U. A TSN 206 S mass-spectrometer with a 30 cm radius of curvature magnet, Hall probe control, automatic peak switching and on-line computer was used for the isotope ratio measurements. Uncertainties in the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios are 0.6–0.8%, at the 95% confidence level, except for samples Bl and Cl where they are about 1%. Similarily uncertainties in the $^{207}Pb/^{206}Pb$ ratios are about 0.1% and 0.15%, respectively. Concordia – discordia analyses were made following Ludwig (1980).

Results and Discussion

The analytical results are listed in Table 1. There is very little correlation between U content and grain size but a strong correlation between U content and paramagnetic susceptibility, and U content and common Pb content. The two U/Pb age calculations are variably discordant for the different zircon fractions. A strongly linear trend is obtained when the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios are plotted on a concordia diagram (Wetherill 1956, Fig. 2a). The extrapolated regression through these 13 points intersects the concordia curve at 2,752±20 Ma (upper intercept) and 1,122±56 Ma (lower intercept) respectively, with MSWD=17.1.

The simplest interpretation of such a line would be that of a two stage process in which the zircons crystallized at the time indicated by the upper intercept and then lost

Table 1. U and Pb isotope ratio analysis for zircon samples taken from the Kathleen Valley granophyre

No.	Fraction: Sieve (Mesh)	Fraction: Magnetic property[a] (Tilt angle)	Weight mg	Concentr. Pb (ppm)	Concentr. U (ppm)	Atomic ratios 206Pb/204Pb	Atomic ratios 206Pb/238U	Atomic ratios 207Pb/235U	Atomic ratios 207Pb/206Pb	Apparent ages (Ma) 206Pb/238U	Apparent ages (Ma) 207Pb/235U	Apparent ages (Ma) 207Pb/206Pb	Discordance %[c]
B9	60–105	1/2°	11	114	212	1609	0.4750	12.005	0.18330	2505	2605	2683	17
B8HP[b]	60–105	1/2–1°	6.0	117	218	1448	0.4673	11.734	0.18211	2472	2583	2672	19
D9HP	140–200	1/2°	2.0	115	220	2441	0.4612	11.655	0.18328	2445	2577	2683	17
D9	140–200	1/2°	12	114	217	2055	0.4612	11.589	0.18225	2445	2572	2673	20
C8	105–140	1/2–1°	8.6	145	273	1338	0.4609	11.522	0.18131	2444	2566	2665	20
B8	60–105	1/2–1°	16	150	283	1053	0.4563	11.398	0.18115	2423	2556	2663	21
B7HP	60–105	1–2°	5.6	165	316	1178	0.4484	11.103	0.17957	2388	2532	2649	24
G8	270–420	1/2–1°	11	141	282	1176	0.4371	10.595	0.17581	2328	2488	2614	28
A5-9HP	+60	3°	6.0	187	370	674	0.4220	10.181	0.17495	2270	2451	2605	32
D5	140–200	3–4°	15	192	402	877	0.4057	9.399	0.16804	2195	2378	2538	40
F4	230–270	4–5°	14	278	684	596	0.3369	7.229	0.15561	1872	2140	2408	57
B1	60–150	7–8°	12	368	910	343	0.3142	6.257	0.14444	1761	2012	2281	64
C1	105–140	7–8°	11	352	932	331	0.2959	5.873	0.14396	1671	1957	2275	69

[a] Tilt angle refers to the dip angle of the Frantz Isodynamic separator run at 1.85 amp. 10° slope
[b] B8HP implies the same zircon fraction as B8 but hand picked to get pure, least metamict zircon
[c] Approximate. Calculated from measured displacement along approximate two stage discordia

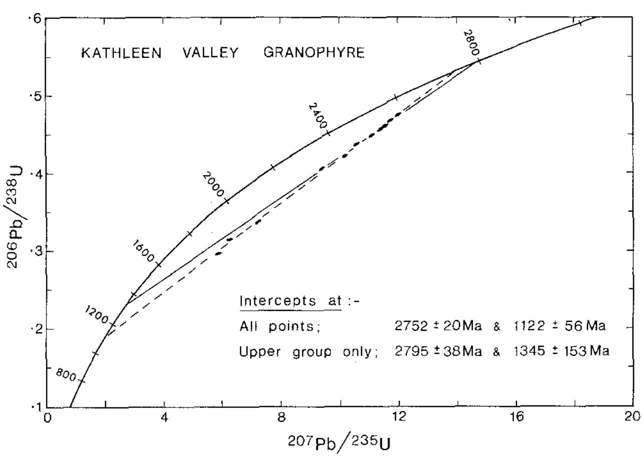

Fig. 2. $^{206}Pb/^{238}U$ v. $^{207}Pb/^{235}U$ concordia diagram for zircon samples from the Kathleen Valley Granophyre

considerable radiogenic Pb (or possibly gained U) at the time indicated by the lower intercept. Figure 2a indicates that, assuming the simple two stage model, from 15% to 70% Pb loss has occurred. As usually occurs (Silver and Deutch 1963) there is a strong correlation between Pb loss and U content. However, the regression analyses also shows that the displacement of the points about the best fit discordia line is more than 4 times greater than what can be attributed to experimental error alone. Therefore another geological factor must be present to cause this excess scatter.

In general there are two possible causes for behaviour. One is that the original zircons are contaminated with some older zircon inherited from the source material. This problem is considered to be most unlikely as: (1) no older zircon cores or fragments are apparent in any of the grains examined; (2) in this large gabbroic-sill environment zircon did not reach saturation and crystallize out until the late granophyric differentiation stage was eventually reached, by which time any contaminant zircons should have been thoroughly worked over and resorbed; (3) the sill was intruded into a mafic-ultramafic mass of similar age which probably has no zircons to supply during the differentiation process.

The second possible cause of scatter is that another geological event has produced a second episode of variable Pb loss at a time considerably different from the two intercept ages already deduced. Figure 2a suggests that such a second Pb loss would be minor compared to the clearly observable lead loss pattern already discussed and would have relatively small, although significant, effects on the position of the line and the two intercept ages derived. Nevertheless it proves to be fruitful to resolve the problem as far as it is possible to go.

Usually the zircon fractions with the highest U and which would show the greatest discordance after the major lead loss event, are, in general, those most likely to show the greatest Pb loss under similar circumstances at any subsequent time (Gebauer and Grunenfelder 1976). Thus the lower points on Fig. 2 are those most likely to show the greatest departure from the true major discordia line. If the upper 8 and the 10th points are regressed together without the lower 3 and the 5th points a much better fit is obtained with the actual scatter of points reducing to 2.5 times the experimental uncertainties alone. This regression should therefore be much less affected by the second Pb loss event and should produce more reliable intercepts on concordia for the crystallization and major disturbance ages. These intercepts are 2,795±38 Ma and 1,343±153 Ma respectively (Fig. 2., Table 2). The above exercise results in the four discarded points obviously plotting under the new discordia line, and emphasises that the second postulated smaller disturbance being recorded occurred after the major one. One third of the remaining departure from linearity is due to the downward displacement of the one point D9 HP (see the regression of 8 points in Table 2). However it is considered imprudent to further discard such minor deviants.

Table 2. Results of regressions of selected zircon analyses and the age intercepts with concordia

No. of points	Upper intercept Ma	Lower intercept Ma	MSWD	Comment
13	2,752 ± 20	1,122 ± 56	17.1	All samples
9	2,795 ± 38	1,345 ± 153	6.2	3 lower and 5th lower points omitted
8	2,790 ± 30	1,335 ± 123	3.8	As above

Table 3. The late Archaean tectonic cycle of Cooper et al. (1978) with new greenstone, zircon age, time of mid Proterozoic major zircon lead loss and periods of documented Phanerozoic uplifts

Event	Time	Reference
Adjacent Regional Unconformities	Holocene Lower Cretaceocs Triassic Carboniferous Cambrian	Playford et al. (1975)
Subtle heating or critical erosion level	1,345 ± 153	This work
Aplitic leucotonalite	2,474 + 14	Cooper et al. (1978)
Pegmatite 2	2,481 + 18	Roddick et al. (1976)
Second Deformation D2		Platt et al. (1978)
Erosion-Mt Keith Biotite Ages	2,565 + 15	Roddick et al. (1976)
Lawlers Leucogranite (Adamellite)	2,576 + 14	Cooper et al. (1978)
Pegmatite 1	2,588 + 18	Cooper et al. (1978)
First Deformation D1		Platt et al. (1978)
Jones Creek-Lawlers Conglomerates Cover removal	(1)	
Perseverance Gneiss	2,625 + 34	Cooper et al. (1978)
Mt Keith Granodiorite	2,632 + 17	Roddick et al. (1976)
Lawlers Tonalite	2,652 + 20	Cooper et al. (1978)
Metasediments Greenstones	2,795 ± 38	This work

Length of late Archaean tectonic cycle = 320 ± 40 Ma

The second concordia-discordia upper intercept is now the best estimate of the age of crystallization of the gabbroic sill although it still may be fractionally lower than reality. This result is 43 Ma older than the crude number obtained by regressing all of the zircon points and 77 ± 63 Ma older than the 2,718 ± 50 Ma age obtained by the scattered fit Rb – Sr whole rock data on the same material (Cooper et al. 1978). The sill is thought to be of similar age to the greenstones which it intrudes. The late Archaean tectonic cycle defined by these workers therefore began about 77 Ma earlier than the previous estimate, and lasted for about 320 Ma, rather than the greater than 240 Ma deduced before. The greenstones, remain the oldest rocks dated in the area, in accord with the relationships suggested by the original mapping (Durney 1972; Platt et al. 1978; Marston and Travers 1976).

McCulloch and Compston (1981) have recently reported a Sm – Nd isochron age of 2,790 ± 30 Ma for possibly equivalent greenstones at Kambalda, 350 km south of Kathleen Valley. These workers clearly warn that the validity of their determination depends on the assumption that the ultramafic, basaltic, felsic porphyry and soda granite samples measured are all essentially of the same age and initial $^{143}Nd/^{144}Nd$ ratio. The similarity of their age calculation with that of our zircon data indicates that their assumption was probably warranted and that a huge, cogenetic belt of greenstones about 400 km long is present in this region of Australia.

Virtually all zircon workers use the upper concordia-discordia intercepts to calculate zircon crystallization ages in a manner similar to above but many prefer to make no interpretation of the meaning of lower intercepts e.g. Pidgeon (1978), Nieuwland and Compston (1981). The fact remains that once a long, linear relationship of the discordia points is established, and the upper discordia-concordia intercept is accepted as the age of crystallization of the zircon, then, for any single population, the lower concordia-discordia intercept must represent a real time of U – Pb chemical redistribution between the zircon grains and their surroundings (The possible diffusion exception is eliminated below). Such an instantaneous chemical adjustment must be triggered by some form of geological disturbance and it remains a real point of interest to establish the nature of that event in all cases.

The lower intercept age of 1,300 Ma obtained from the upper nine points was unexpected from the known geological history and previous dating in the region. For this reason alone it is desirable to look closely for an explanation of its meaning. In this instance it is obligatory to do so because, if the explanation is geological, it could be telling us something new about a supposedly completely cratonized Archaean block that was not suspected before.

The present geological theories associated with the cause of zircon discordia have been summarized by Gebauer and Grunenfelder (1979). These are:

(1) Episodic lead loss due to a later metamorphic event (Wetherill 1956).

(2) Lead loss by continuous diffusion, either simple or exponential e.g. Tilton (1960), Wasserburg (1963).

(3) Lead loss due to extreme weathering (Stern et al. 1966).

(4) Lead loss during tectonic uplift, the dilation model (Goldich et al. 1970; Goldich and Mudrey 1972).

(5) Low temperature zircon annealing not necessarily revealed in mineral assemblages.

(6) Shear recrystallization (Peterman et al. 1980).

The continuous diffusion lead loss processes (2) appear to be excluded from this suite because of the diffusion rate measurements of Shestakov (1972), and the extreme weathering (3) and shear recrystallization (6) situations are not relevant here.

The presence of a later metamorphic heating event with the eastern Yilgarn Block has proved difficult to establish. Close examination of thin sections of the gabbro-granophyre samples show no trace of retrograde reactions from the early low amphibolite facies assemblage. Also, the Rb – Sr isotopic systematics of biotites of the nearby Mt. Keith Granodiorite closed at 2,565 ± 25 Ma (Roddick et al. 1976). As this mass is part of the same local graben of the cratonic block as the gabbro (Fig. 1) it can be argued that none of these rocks have approached 300° C since that time.

Ahmat and de Laeter (1982) report a 1,496 ± 189 Ma olivine, 2 pyroxene, plagioclase, total rock, Rb – Sr isochron age measurement on an approximately 2,700 Ma anorthositic gabbro in the Windimurpa Complex 190 km west of Kathleen Valley. This, Proterozoic age may be incorrect as all the minerals, including the plagioclase, plot to the right of the equivalent total rock sample, suggesting trace contamination by a Rb rich mineral during the mineral separation process. Thus the very low Rb minerals could produce a good linear array that has no age significance (i.e. a mixing line). We are therefore dubious about accepting this result but acknowledge that, if real, it would be a significant factor in our problem.

We are then left with the geological choice of either (5) partial zircon annealing during a low temperature heat pulse that left no petrographical record on the other minerals present; or (4), a period of tectonic uplift and overburden removal in the mid-Proterozoic for which there is also no local evidence. Both of these geological theories have been applied by other authors to similar situations involving Precambrian rocks e.g. (1) Goldich et al. (1970) explained the discordance pattern of 3,600 Ma zircons from Precambrian gneisses in the Minnesota River Valley as being caused by two processes. The first was a heating associated with the intrusion of 2,600 Ma adamellites, while the second, about 100 Ma ago, could not be associated with any known geological event and was attributed to the uplift-dilation process. (2) Peterman et al. (1980) reported that 3,600 Ma zircons in Michigan gneisses lost lead during the 1,750 Ma Penokean Orogeny. 2,750 Ma granite and 2,600 Ma leuco-granites have well defined zircon lower intercepts of about 650 Ma and 850 Ma respectively, but as no local geological heating event could be found to explain these numbers they were attributed to the regional uplift and faulting processes. Thus, currently, other geological information is essential to achieve any understanding of the meaning of zircon discordia lower intercept ages.

As no other post-Archaean activity of any of the above characteristics has been recorded within the Yilgarn Block itself, attention was directed to the adjacent Proterozoic provinces. Despite their great distance from the rocks of interest some apparently relevant information was found. In the eastern part of the Albany-Fraser province, 600 km to the south-east of Kathleen Valley, a granulite facies metamorphism at about 1,300 Ma, followed by the intrusion of slightly younger granitoids, has been established by several workers (Arriens and Lambert 1976; Bunting et al. 1975). Rocks of this type extend for nearly 1,000 km along the south and south-eastern edge of the Yilgarn Block (Doepel 1975). Deep, hot rocks were obviously uplifted and at least partially uncovered along this whole region at this time.

The Gascoyne Province, 500 km to the north and north-west of Kathleen Valley has provided isotopic evidence of migmatization at about 1,700 Ma (de Laeter 1976; Williams et al. 1978), which is also present in the Albany Fraser Province (Bunting et al. 1975), although no 1,300 Ma event has yet been recorded. However, Daniels (1975), has described a major post migmatization uplift, accompanied by erosion of this area. The movement has not been dated directly but, using regional correlations, Daniels (1975) assessed that it occurred "at about 1,400 Ma".

Thus is appears that two provinces, each on opposite sides of the Yilgarn Block, both received some heat input and were subsequently uplifted at about the time indicated by the Kathleen Valley lower discordia intercept. Did the whole Yilgarn Block either move epeirogenically or perhaps undergo a temperature rise at the same time? The time coincidence makes it highly suggestive that at least one of these processes was related to the zircon disturbance many hundreds of kilometres away, but with present day understanding it remains very difficult to say which one it was.

Gee et al. (1980) draw attention to the remarkable topographical flatness of the whole of the Yilgarn Block. They argue that this feature could result from the recent exhumation of a huge early Proterozoic, or even Archaean, peneplain of uncertain age. The zircon lower intercept age of 1,350 Ma may therefore result from a dilation type process which records the uplift and cover removal involved in the formation of such an early peneplain, and would place the time of such a happening in the mid Proterozoic.

It is equally difficult to establish which of the two mechanisms could be related to the proposed second disturbance of the discordia pattern. Evidence is again sought from the geology outside of the Yilgarn Block. To the north Rb – Sr mineral systematics are completely reset in the Eastern Gascoyne Province at 700–800 Ma (Williams et al. 1978) but apparently not in the Western Gascoyne Province (de Laeter 1976). The breakup of Gondwanaland would have involved much heat input and uplift along the rifts far to the south and west in Mesozoic time. The sedimentary basins surrounding the Yilgarn Block indicate several minor epeirogenic movements of which the most significant was in the Cambrian (Tectonic Map of Australia, 1970). Regional uplifts followed by denundation, or exhumation of the present day erosional surface, may, through further dilation processes, have contributed to the discordant pattern obtained. Thus although Pb appears to have been lost from the most U rich minerals by any one or all of the aforementioned events the data are insufficient to indicate an exact cause of the array.

References

Ahmat AL, de Laeter JR (1982) Rb – Sr isotopic evidence for Archean-Proterozoic crustal evolution of part of the central Yilgarn Block, Western Australia: constraints on the age and source of the Windimurra Gabbroid. J Geol Soc Aust 29:177–190

Arriens PA (1971) The Archaean geochronology of Australia. Geol Soc Aust Spec Publ 3:11–23

Arriens PA, Lambert IB (1976) On the age and strontium isotopic geochemistry of granulite facies rocks from the Fraser Range, Western Australia and the Musgrave Ranges, Central Australia. Geol Soc Aust Spec Publ 2:377–388

Bunting JA, de Laeter JR, Libby WG (1975) West Aust Geol Surv Ann Rp for 1974:117–126

Cooper JA, Nesbitt RW, Platt JP, Mortimer GE (1978) Crustal development in the Agnew region, Western Australia, as shown by Rb/Sr isotopic and geochemical studies. Precamb Res 7:31–59

Daniels JL (1975) Palaeogeographic development of Western Australia. In the Geology of Western Australia, Geol Surv of West Aust Mem 2:437–445

de Laeter JL (1976) Rb – Sr whole rock and mineral ages from the Gasgoyne Province. West Aust Geol Surv Ann Rp for 1975:126–130

Doepel JJG (1975) Albany-Fraser Province. Geol Surv of West Aust Mem 2:94–101

Durney DW (1972) A major unconformity in the Archaean, Jones Creek, Western Australia. J Geol Soc Aust 19:251–259
Gebauer D, Grunenfelder M (1976) U–Pb zircon and Rb–Sr whole rock dating of low grade metasediments. Example: Montagne Noire (Southern France). Contrib Mineral Petrol 59:13–32
Gee RD, Baxter JL, Wilde SA, Williams IR (1981) Crustal development in the Archaean Yilgarn Block, Western Australia. In: Archaean Geology. Spec Publ Geol Soc Aust 7:57–69
Goldich SS, Hedge CE, Stern TW (1970) Age of the Morton and Montevideo Gneisses and related rocks, Southern Minnesota. Bull Geol Soc Am 81:3671–3696
Goldich SS, Mudrey JR (1972) Dilatancy model for discordant U–Pb zircon ages. In: Recent Contributions to Geochemistry and Analytical Chemistry, Tugaranov, A.I. (ed). Wiley, New York, 415–418
Krogh TE (1973) A low contamination method for the hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochim Cosmochim Acta 37:485–494
Ludwig KR (1980) Calculation of uncertainties of U–Pb isotopic data. Earth Plan Sci Let 46:212–220
Marston RJ, Travers GR (1976) Stratigraphic implications of heterogenous deformation in the Jones Creek Conglomerate (Archaean), Kathleen Valley, Western Australia. J Geol Soc Aust 23:141–156
McCulloch MT, Compston W (1981) Sm–Nd age of Kambalda and Kanowna greenstones and heterogeneity in the Archaean mantle. Nature 294:322–327
McIntyre GR, Brooks CR, Compston W, Turek A (1966) The statistical assessment of Rb/Sr isochrons. J Geophys Res 71:5459–5468
Nieuwland DA, Compston W (1981) Crustal evolution in the Yilgarn Block near Perth, Western Australia. In: Archaean Geology. Geol Soc Aust Spec Publ 7:159–172
Peterman ZE, Zartman RE, Sims PK (1980) Tonalitic Gneisses of early Archaean Age from northern Michigan. Geol Soc Am Spec Pap 182:125–134
Pidgeon RT (1978) 3450 m.y. old volcanics in the Archaean layered greenstone succession of the Pilbara Block, Western Australia. Earth Plan Sci Let 37:421–428
Platt JP, Rutland RWR, Allchurch PD (1978) Archaean tectonics in the Agnew supracrustal belt, Western Australia. Precamb Res 7:3–30
Playford PE, Cope RN, Cockbain AE, Low GH, Lowry DC (1975) Phanerozoic. In: The Geology of Western Australia. Geol Surv West Aust Mem 2:223–436
Roddick JC, Compston W, Durney DW (1976) The radiometric age of the Mt. Keith Grandiorite, a maximum age estimate for an Archaean greenstone sequence in the Yilgarn Block, Western Australia. Precamb Res 3:55–78
Silver LT, Deutsch S (1963) Uranium lead variations in zircon: a case study. J Geol 71:747–758
Stern TW, Goldich SS, Newell MF (1966) Effects of weathering on the U–Pb ages of zircons from the Morton Gneiss, Minnesota. Earth Plan Sci Let 1:369–371
Shestakov GI (1972) Diffusion of lead in monazite zircon sphene and apatite. Trans Geochimiya 10:1197–1202
Tilton GR (1960) Volume diffusion as a mechanism for discordant lead ages. J Geophys Res 65:2933–2945
Turek A (1966) Rubidium Strontium studies in the Kalgoorlie Norseman Area, Western Australia. Ph D thesis ANU (unpubl)
Wasserburg GJ (1963) Diffusional processes in lead-uranium systems. J Geophys Res 68:4823–4846
Wetherill GS (1956) Discordant uranium-lead ages I. Trans Am Geophys Un 37:320–326
Williams JS, Elias M, de Laeter JR (1978) Geochronology and evolution of the Eastern Gascoyne Province and the adjacent Yilgarn Block. Geol Surv of West Aust An Rp for 1977:50–56

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