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U-Pb dating of overpressure veins in late Archean shales reveals six episodes of Paleoproterozoic deformation and fluid flow in the Pilbara Craton

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Drill-hole information

Samples were collected from two drill-holes from the southern Pilbara Craton, Western Australia (Fig. 1A). Drill-hole ABDP9 was drilled in 2004 as part of the Deep Time Drilling Project (DTDP) of the Astrobiology Drilling Program (ADP) of the NASA Astrobiology Institute (NAI) (Anbar et al., 2007). The project also involved the University of Western Australia, Hamersley Iron, SIPA Resources International, Geological Survey of Western Australia and Randolph Resources. The aim of the drill-hole was to "*obtain drill core free of modern contamination and weathering effects for biogeochemical analysis to characterize the nature of life and its environment in the late Archean, shortly before the rise of atmospheric oxygen*" (Anbar et al., 2007). The drill-hole, which was located at 21° 59' 29.5" S, 117° 25' 13.6" E, recovered ~1000 m of core spanning the base of the Dales Gorge Member of the Brockman Iron Formation to the Paraburdoo Member of the Wittenoom Formation (Fig. 1B). One half of the core is stored at the School of Earth and Space Exploration at Arizona State University, USA, whereas the other half is archived at the Perth Core Library in Western Australia.

Drill-hole DDH186 was drilled in 1977 by Hamersley Exploration Pty Ltd to target the Marra Mamba Iron Formation (Davy and Hickman, 1988). Drill-hole DDH186 intersected the lower part of the Marra Mamba Iron Formation (Hamersley Group) and the upper part of the Roy Hill Shale Member (Fortescue Group). The location of the drill-hole is shown in Figure 1A (117" 55' E and 22" 24' S; AMG SF50, 594600E and 7522600N). DDH186 was drilled to 207.5 m normal to the bedding and unweathered rocks were recovered between 54.0 m and 207.5 m. Samples used in this study were collected from the Roy Hill Shale Member, between 141.95 m to 207.50 m.

SHRIMP mount identification

1. Mount BR13-20, plugs C, I & L (vein), H (detrital); ABDP9 135.02-.10 m – monazite in vein
2. Mount BR13-13, plugs C & F; ABDP9 141.87-.94 m – xenotime in sigmoidal lenses
3. Mount BR13-13, plugs A, B, D & E; ABDP9 182.12-.25 m – monazite in vein
4. Mount BR13-20, plugs E & K; ABDP9 243.20-.30 m – monazite in vein
5. Mount BR13-20, plug F; ABDP9 333.42-.45 m - monazite, xenotime in matrix
6. Mount BR13-20, plugs A, B, D & J; ABDP9 364.03-.22 m – monazite in vein
7. Mount BR19-02, plugs C & D; DDH186, 183.00 m – monazite in vein

U-Pb analytical procedures

Monazite and xenotime were analysed for U-Pb dating with the Sensitive High-Resolution Ion MicroProbe (SHRIMP-II) instrument at the John De Laeter Centre, Perth, Western Australia. Grains for analysis were identified in polished thin sections, and 3 mm diameter plugs were extracted from the thin sections with a hollow-core rotary drill and mounted in 25 mm diameter epoxy discs. The mounts were cleaned and gold coated before each analytical session. Monazite and xenotime standards were set into separate mounts and gold coated simultaneously with sample mounts. Standard and sample mounts were loaded together into the SHRIMP for concurrent analysis during each of the four analytical sessions.

Instrument setup followed protocols for small-spot, in-situ analysis of monazite and xenotime developed in Rasmussen et al. (2001), Fletcher et al. (2000; 2004; 2010). A primary beam of O_2^- ions was focused through a 50 µm Kohler aperture to produce an oval 10 µm wide spot on the sample surface with a current of 0.3 nA. The secondary ion system was focused through a 100 µm collector slit onto an electron multiplier to produce mass peaks with flat tops and a mass resolution of >5400 in all sessions. Background counts from scattered ions were reduced using a flight retardation lens, which is known to cause slight session-dependent instrumental mass fractionation (IMF) of Pb isotopes (Rasmussen et al., 2008). IMF corrections were applied to all analyses.

Data were collected in sets of 8 scans, with standard monazite or xenotime analysed every 4-6 sample analyses. Count times per scan for Pb isotopes 204, background position 204.045, 206, 207 and 208 were 10s, 10s, 10s, 30s and 10s, respectively. Monazite was analysed with a 13-peak run table as defined in Fletcher et al. (2010), which includes mass stations for the estimation of La, Ce and Nd ($REEPO_2^+$), and Y ($YCeO^+$). Measurements on monazite standards FRENCH, Z2234 and Z2908 (see Fletcher et al., 2010 for details) were done concurrently for Pb/U and Pb/Th calibration (FRENCH), 204 a.m.u. isobar corrections, IMF corrections and matrix corrections required for variable U, Th, Y and Nd contents. Raw data were processed using a customised task file for the SQUID2 (v. 2.50.12.03.08) add-in for Excel 2003 (Ludwig, 2009), and plotted using the ISOPLOT (v. 3.76.12.02.24) add-in (Ludwig, 2008). Common Pb corrections were made from ^{204}Pb measurements corrected for the 204 a.m.u isobar, following the procedure in Fletcher et al. (2010). Common Pb composition was assumed to be that of Broken Hill lead, a common environmental contaminant in Australia, with a composition equivalent to that at 1.6 Ga in the two-stage evolution model of Stacey and Kramers (1975). Since all analyses have low ^{204}Pb contents and yield mid to late-Proterozoic ^{207}Pb/^{206}Pb ages, the choice of Broken Hill lead as common Pb will not have significant effects on results. IMF and matrix corrections were done using an Excel spreadsheet developed by I. R. Fletcher.

Xenotime was analysed with a 9-peak run table following analytical protocols in Fletcher et al. (2000, 2004). Pb/U calibrations and matrix corrections for U and Th contents were based on concurrent measurements of the standards MG-1 (Fletcher et al., 2004) and z6413 (“Xeno1”; Stern and Rayner, 2003). Pb/Th was determined indirectly, using a fixed Th/U calibration (Fletcher et al., 2004). Matrix corrections for REE assumed the samples to have REE abundances similar to Xeno1. Matrix corrections were done using an Excel spreadsheet developed by I. R. Fletcher.

Data are presented in table with 1σ errors. Individual analysis errors are quoted in text at 1σ, and pooled ages are quoted in text and figures at 95% confidence levels. A minimum spot-to-spot external precision of 1% (1σ) was assumed for standard analyses in all sessions and propagated to U-Pb measurements on all samples of both monazite and xenotime. Data were collected during four sessions, including one session for xenotime analysis. The sessions are indicated in the data table. The following precisions on mean calibration values were obtained in each session: session 1 (monazite) = 0.3% (n = 10, MSWD = 1.1, external precision = 1.0%), session 2 (xenotime) = 0.8% (n = 7, MSWD = 3.3, external precision = 1.6%), session 3 (monazite) = 0.3% (n = 6, MSWD = 1.6, external precision = 1.0%) and session 4 (monazite) = 0.6% (n = 10, MSWD = 4.3, external precision = 1.5%).

Sample descriptions and results

ABDP9 87B, 135.02-.1 m (Mount McRae Shale)
In this sample, four discrete grains of monazite were identified and analysed; three from a vein and one from the finer-grained matrix. All grains are less than 50 µm across, irregular and inclusion-rich. Analyses on all grains have low U (<200 ppm), whereas Th is much higher in the matrix-hosted grain (3.0-4.2 %) than in the vein-hosted grains (359-4164 ppm). Two analyses on the matrix-hosted grain yielded consistent, slightly discordant data with a mean $^{207}Pb/^{206}Pb$ age of 2514 ± 18 Ma (n = 2, MSWD = 0.67) (Fig. 3A, Table DR1). Ten analyses from the three vein-hosted grains yield variably discordant data with consistent $^{207}Pb/^{206}Pb$ ages, with a mean $^{207}Pb/^{206}Pb$ age of 2192 ± 24 Ma (n = 9, MSWD = 1.00). Both ages are interpreted as dating monazite growth, with the older matrix age possibly including a detrital component.

ABDP9 86A, 141.87-.94 m (Mount McRae Shale)
Three grains of xenotime were identified and analysed in this sample. All three are platy poikiloblasts up to 250 µm across, aligned parallel to bedding. Grain edges are ragged and inclusions are in most cases also aligned with bedding, typical of growth overprinting the rock fabric. In grain BR13-13C.1, inclusions occur as flakes aligned perpendicular to the length of the grain. Grain BR13-13C.2 is lens-shaped, and has margins intergrown with nickel sulfide. Analyses contain around 500-900 ppm U and 2700-9000 ppm Th. Six out of seven analyses on grain BR13-13C.2, excluding one concordant analysis with a slightly younger age, yield a mean $^{207}Pb/^{206}Pb$ age of 2043 ± 11 Ma (n = 6, MSWD = 0.8) (Fig. 3B, Table DR2). Analyses on the other two grains yield a mean $^{207}Pb/^{206}Pb$ age of 1658 ± 16 Ma (n = 8, MSWD = 1.1). The two ages are interpreted as dating separate episodes of xenotime growth.

ABDP9 75, 182.12-.25 m (Mount McRae Shale)
Five grains of monazite were analysed in this sample. All grains are platy, 100 to 200 µm long, and poikiloblastic, with fine aligned inclusions aligned parallel to bedding in the host rock. Analyses contain around 100-600 ppm U and 400-4600 ppm Th. Excluding concordant analysis BR13-13A.1-3 with a $^{207}Pb/^{206}Pb$ age of 2317 ± 25 Ma (1σ), analyses from all five grains define a single population with a $^{207}Pb/^{206}Pb$ age of 2211 ± 8 Ma (n = 29, MSWD = 1.3) (Fig. 3C; Table DR3). The outlier is equivalent in age to monazite grains in sample ABDP9 27B (see below), whereas the main population is equivalent in age to monazite in samples ABDP9 87B, ABDP9 44B and ABDP9 23A (see below).

ABDP9 44B, 243.2-.3 m (Wittenoom Formation)
From this sample, two poikiloblasts of monazite were analysed. The poikiloblasts are associated with fine felsic laminations in the host rock. Both grains are about 200 µm long, platy and irregular, flattened and with inclusions aligned parallel to the laminations in the host rock. Analyses contain around 100-200 ppm U and 200-2600 ppm Th. All analyses yield a mean $^{207}Pb/^{206}Pb$ age of 2196 ± 11 Ma (n = 11, MSWD = 0.4) (Fig. 3D; Table DR4).

ABDP9 27B, 333.42-.45 m (Wittenoom Formation)
Within a 1 mm by 1 mm area of polished thin section, this sample contains three poikiloblasts of monazite, one of which lies adjacent to and in contact with a poikiloblast of xenotime. The monazite poikiloblasts are about 200 µm across, irregular and rich in inclusions, some of which are aligned with bedding in the host sediment. Two of the poikiloblasts are connected by a thin plate of monazite with feathery outgrowths, 800 µm long extending along bedding. Analysis spots were selected on the few areas larger than 10 µm that are inclusion-free. Analyses on the monazite poikiloblasts contain 58-238 ppm U and 3-206 ppm Th, with variations of Th/U from 0.01 to 3.4 within individual grains. These Th

contents are unusually low compared to monazite from other samples. All analyses from the three monazite grains yield a mean $^{207}Pb/^{206}Pb$ age of 2307 ± 15 Ma (n = 7, MSWD = 0.7) (Fig. 3E; Table DR5).

The grain of xenotime is about 600 µm by 300 µm, with an approximately blocky outline filled with fine dendritic and feathery outgrowths around a loosely consolidated core. A weak alignment with bedding is visible in the xenotime outgrowths. The xenotime is much richer in U and Th than the monazite, containing around 900-2900 ppm U and 400-2700 ppm Th, with Th/U from 0.4 to 1.7. Excluding three concordant outliers with slightly younger ages, the remainder yielded a mean $^{207}Pb/^{206}Pb$ age of 2097 ± 5 Ma (n = 12, MSWD = 0.6). The three younger analyses all derive from spots closer to the edges of the xenotime poikiloblast, and are equivalent in age, yielding a mean $^{207}Pb/^{206}Pb$ age of 2052 ± 9 Ma (n = 3, MSWD = 0.3) (Fig. 3E; Table DR5). The discrete age cluster is interpreted to represent the time of an overgrowth on the xenotime poikiloblast, and the age estimate is equivalent to that of a grain of xenotime in sample ABDP9 86A. Together, this sample records two or three episodes of unrelated phosphate growth, two in xenotime and one in monazite. The latter is equivalent in age with a single age outlier from monazite in sample ABDP9 75.

ABDP9 23A, 363.03-.22 m (Wittenoom Formation)

Five poikiloblastic grains of monazite were analysed in this sample (Fig. 3F; Table DR6). Grains are associated with fine (<100 µm thick) felsic laminations in the host rock, and are platy, aligned with the laminations, and rich in inclusions aligned with the laminations. Analyses yield U contents of about 90-250 ppm and Th contents of about 400-2000 ppm. Analyses on individual grains yielded variable age estimates. Analysis BR13-20B.1-3 yielded an imprecise age and is excluded from population analysis. Excluding another three, slightly younger analyses, the remaining data from four out of five grains yield a mean $^{207}Pb/^{206}Pb$ age of 2289 ± 16 Ma (n = 11, MSWD = 1.4). The three younger outliers, each deriving from a separate grain, are equivalent in age with a mean $^{207}Pb/^{206}Pb$ age of 2195 ± 21 Ma (n = 3, MSWD = 0.9). Two of these younger ages are from spots on the ends of platy monazite grains that yielded ca. 2289 Ma ages. The younger age may represent a discrete stage of monazite overgrowth or modification on grains originally grown at ca. 2289 Ma. This is supported by equivalent ages of monazite in samples ABDP9 87B, ABDP9 75 and ABDP9 44B.

DDH186, 183.0 m (Roy Hill Shale Member, Jeerinah Formation)

Two large monazite porphyroblasts identified in this sample display elongate outlines (grain 1, 500 µm by 200 µm; grain 2, 250 µm by 100 µm) and are aligned in an overpressure vein. Both monazite porphyroblasts are enclosed in quartz and calcite. The crystals appear to be chemically homogeneous using BSE imaging, and contain rare mineral inclusions. A total of 22 analyses were obtained from the two monazite grains (Table DR7). One analysis, which has a high Th content (5480 ppm) and a Th/U ratio of 88, yields discordant data that was excluded from pooled age calculation. The remaining analyses yield concordant or near-concordant data (Fig. 3G). Their U and Th concentrations range from 52-868 ppm and 16-4125 ppm, respectively, with Th/U ratios between 0.1 and 16 (average 3.3). The most concordant analyses (within ± 5% disc.) have $^{207}Pb/^{206}Pb$ dates ranging from 2379 Ma to 2438 Ma with a weighted mean date of 2407 ± 9 Ma (n = 18, MSWD = 0.68). If the three near-concordant (6-7% disc.) analyses are included, a slightly more precise mean date is achieved: 2407 ± 8 Ma (n = 21, MSWD = 0.67), which is regarded as the best estimate of the age of monazite growth.

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Table DR1. U-Pb data for monazite in drill-hole ABDP9 (135.02–.10 m), Mount McRae Shale

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Ages (Ma) ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Disc. (%)
Grains in vein (2192 ± 24 Ma, *n* = 9, MSWD = 1.00)													
1320C.1-2	75	1332	18	0.17	2.642	0.042	0.1375	0.0020	2070	28	2195	26	6
1320C.1-3	28	1480	53	1.91	2.486	0.059	0.1373	0.0055	2180	44	2194	70	1
1320C.1-4	36	703	20	1.46	2.493	0.081	0.1326	0.0057	2174	60	2133	75	-2
1320I.1-1	66	325	4.9	0.11	2.376	0.052	0.1362	0.0018	2265	42	2179	23	-4
1320I.1-2	54	649	12	0.26	2.518	0.049	0.1418	0.0042	2156	35	2249	51	4
1320L.1-1	77	759	10	0.24	2.743	0.043	0.1375	0.0032	2004	27	2196	41	9
1320L.1-2	68	1241	18	0.44	2.589	0.042	0.1384	0.0024	2105	29	2207	30	5
1320L.1-3	68	2009	30	1.23	2.670	0.071	0.1402	0.0035	2051	47	2230	43	8
1320L.1-4	26	4164	160	1.04	2.488	0.064	0.1255	0.0051	2178	48	2036	71	-7
Grain in matrix (2514 ± 18 Ma, *n* = 2, MSWD = 0.67)													
1320H.1-1	154	29840	194	-0.06	2.172	0.028	0.1649	0.0013	2442	26	2507	13	3
1320H.1-2	190	42420	223	-0.22	2.215	0.037	0.1664	0.0013	2402	34	2522	13	5
Rejected, disc. >10%													
1320C.1-1	59	359	6.1	0.00	2.762	0.050	0.1420	0.0022	1992	31	2252	27	12

Pb* indicate radiogenic Pb

f_{206} is the proportion of common (unradiogenic) Pb in ^{206}Pb, determined using the measured ^{204}Pb/^{206}Pb and a common Pb composition from the Stacey and Kramers (1975) model at the approximate age of the sample.

^{238}U/^{206}Pb* and ^{207}Pb*/^{206}Pb* ratios and dates have been corrected for common Pb.

Disc. is apparent discordance, as 100(t[^{207}Pb*/^{206}Pb*] - t[^{238}U/^{206}Pb*]) / t[^{207}Pb*/^{206}Pb*].

Analyses are sorted by descending t[^{207}Pb*/^{206}Pb*] except for those excluded in age calculation due to large discordance (and/or high common Pb).

Session calibration precisions and external spot-to-spot errors provided in analytical procedures section.

Same footnotes apply to Tables DR2–7

Table DR2. U-Pb data for xenotime in ABDP9 (141.87–.94 m), Mount McRae Shale

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Ages (Ma) ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Disc. (%)
Older group (2043 ± 11 Ma, *n* = 6, MSWD = 0.79)													
1313C.2-1	822	4160	5.2	0.03	2.684	0.057	0.1250	0.0014	2041	37	2029	20	-1
1313C.2-2	765	3964	5.4	0.11	2.698	0.058	0.1263	0.0009	2032	37	2048	12	1
1313C.2-3	594	3513	6.1	0.10	2.757	0.063	0.1257	0.0017	1995	39	2039	24	3
1313C.2-4	829	4133	5.1	0.03	2.661	0.057	0.1268	0.0008	2057	37	2054	11	0
1313C.2-5	917	5098	5.7	0.08	2.882	0.059	0.1262	0.0008	1920	34	2046	11	7
1313C.2-7	870	5021	6.0	0.08	2.986	0.077	0.1247	0.0009	1862	41	2025	12	9
Younger group (1658 ± 16 Ma, *n* = 8, MSWD = 1.14)													
1313C.1-1	557	2724	5.1	0.03	3.448	0.080	0.1021	0.0010	1642	34	1663	17	1
1313C.1-2	543	3155	6.0	0.03	3.509	0.081	0.1035	0.0010	1616	33	1688	17	5
1313C.1-3	629	3613	5.9	0.06	3.370	0.076	0.1014	0.0016	1675	33	1651	29	-2
1313C.1-4	840	5304	6.5	0.18	3.525	0.076	0.0997	0.0014	1610	30	1618	26	1
1313F.1-1	533	5419	11	0.49	3.402	0.079	0.1007	0.0015	1661	34	1638	28	-2
1313F.1-2	501	5590	12	0.04	3.507	0.083	0.1024	0.0011	1617	34	1668	19	3
1313F.1-3	573	8558	15	0.34	3.500	0.081	0.1004	0.0018	1620	33	1631	32	1
1313F.1-4	618	9007	15	0.85	3.313	0.076	0.1001	0.0017	1700	34	1626	32	-5
Outlier													
1313C.2-6	783	4293	5.7	0.78	2.870	0.061	0.1202	0.0014	1927	35	1959	21	2

Table DR3. U-Pb data for monazite in ABDP9 (182.12–.25 m), Mount McRae Shale

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios $^{238}U/^{206}Pb^*$	±	$^{207}Pb^*/^{206}Pb^*$	±	Ages (Ma) $^{238}U/^{206}Pb^*$	±	$^{207}Pb^*/^{206}Pb^*$	±	Disc. (%)
Older group (2211 ± 8 Ma, *n* = 29, MSWD = 1.3)													
1313A.1-1	162	4558	28	0.03	2.493	0.043	0.1397	0.0014	2174	32	2223	18	2
1313A.1-2	337	858	2.5	0.07	2.499	0.030	0.1360	0.0013	2170	22	2177	16	0
1313A.1-4	261	1655	6.3	0.00	2.430	0.049	0.1400	0.0012	2222	37	2227	14	0
1313A.1-5	226	3554	16	0.19	2.543	0.033	0.1335	0.0022	2138	24	2145	29	0
1313A.2-1	201	2562	13	0.45	2.489	0.036	0.1338	0.0047	2177	26	2148	61	-1
1313A.2-2	118	2758	23	0.26	2.473	0.037	0.1357	0.0031	2189	28	2172	40	-1
1313A.2-3	207	1965	9.5	-0.07	2.525	0.043	0.1387	0.0015	2151	31	2211	18	3
1313A.2-4	208	1245	6.0	0.03	2.462	0.038	0.1400	0.0013	2197	29	2227	16	1
1313A.2-5	416	388	0.9	-0.03	2.395	0.028	0.1399	0.0010	2249	22	2225	13	-1
1313A.2-6	210	1571	7.5	0.23	2.469	0.032	0.1371	0.0015	2192	24	2190	20	0
1313A.2-7	193	762	3.9	-0.07	2.372	0.031	0.1391	0.0014	2268	25	2216	17	-2
1313B.1-1	191	692	3.6	0.03	2.436	0.032	0.1384	0.0014	2217	25	2208	17	0
1313B.1-2	138	1403	10	0.09	2.320	0.040	0.1385	0.0015	2310	34	2208	19	-5
1313B.1-3	206	1031	5.0	0.20	2.418	0.041	0.1378	0.0015	2231	32	2200	19	-1
1313B.1-4	229	1692	7.4	0.07	2.393	0.040	0.1373	0.0013	2251	31	2193	17	-3
1313B.1-5	174	885	5.1	0.05	2.521	0.079	0.1399	0.0014	2154	57	2226	18	3
1313B.1-6	111	1569	14	0.02	2.335	0.050	0.1398	0.0026	2297	41	2225	32	-3
1313D.1-1	511	574	1.1	0.06	2.544	0.029	0.1399	0.0010	2137	21	2226	12	4
1313D.1-2	222	913	4.1	0.45	2.477	0.041	0.1380	0.0017	2186	31	2203	21	1
1313D.1-3	237	1431	6.0	0.11	2.367	0.046	0.1374	0.0013	2272	37	2195	16	-4
1313D.1-4	584	1154	2.0	0.06	2.328	0.036	0.1407	0.0010	2304	30	2236	12	-3
1313D.1-5	286	665	2.3	0.12	2.470	0.050	0.1403	0.0013	2191	37	2231	16	2
1313D.1-6	250	1724	6.9	0.01	2.377	0.039	0.1374	0.0012	2264	31	2195	16	-3
1313E.1-1	175	2740	16	0.04	2.579	0.051	0.1378	0.0016	2113	35	2199	20	4
1313E.1-2	242	1727	7.1	0.13	2.611	0.043	0.1390	0.0014	2090	29	2214	17	6
1313E.1-3	194	2289	12	0.31	2.537	0.051	0.1354	0.0017	2142	37	2169	21	1
1313E.1-4	326	869	2.7	0.03	2.363	0.051	0.1399	0.0011	2275	41	2226	14	-2
1313E.1-5	405	1183	2.9	0.04	2.361	0.046	0.1377	0.0010	2276	38	2199	13	-4
1313E.1-6	164	1044	6.3	0.15	2.364	0.040	0.1376	0.0022	2274	32	2197	28	-4
Outlier													
1313A.1-3	279	1238	4.4	0.19	2.254	0.028	0.1475	0.0021	2367	24	2317	25	-2

Table DR4. U-Pb data for monazite in ABDP9 (243.2–.3 m), Wittenoom Formation

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios				Ages (Ma)				Disc. (%)
					$^{238}U/^{206}Pb^*$	±	$^{207}Pb^*/^{206}Pb^*$	±	$^{238}U/^{206}Pb^*$	±	$^{207}Pb^*/^{206}Pb^*$	±	
Main group (2196 ± 11 Ma, *n* = 11, MSWD = 0.44)													
1320E.1-1	167	383	2.3	0.02	2.660	0.034	0.1376	0.0012	2057	22	2198	15	6
1320E.1-2	139	234	1.7	0.06	2.486	0.051	0.1361	0.0014	2179	38	2178	18	0
1320E.1-3	116	1090	9.4	0.14	2.468	0.043	0.1376	0.0016	2193	32	2197	20	0
1320E.1-4	129	831	6.4	0.26	2.539	0.061	0.1370	0.0031	2141	43	2190	39	2
1320E.1-5	136	733	5.4	0.13	2.695	0.046	0.1384	0.0015	2035	29	2208	19	8
1320E.1-6	201	330	1.6	0.01	2.493	0.040	0.1374	0.0011	2174	29	2194	14	1
1320K.1-1	185	2579	14	0.18	2.762	0.060	0.1378	0.0016	1992	37	2199	20	9
1320K.1-2	138	661	4.8	0.23	2.554	0.043	0.1364	0.0016	2130	31	2182	20	2
1320K.1-3	131	1138	8.7	0.37	2.593	0.054	0.1360	0.0026	2103	37	2177	33	3
1320K.1-4	180	752	4.2	-0.04	2.616	0.053	0.1394	0.0013	2087	36	2219	17	6
1320K.1-5	124	799	6.5	0.06	2.547	0.044	0.1372	0.0015	2135	31	2192	19	3

Table DR5. U-Pb data for monazite and xenotime in ABDP9 (333.42–.45 m), Wittenoom Formation

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Ages (Ma) ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Disc. (%)
Monazite (2307 ± 15 Ma, *n* = 7, MSWD = 0.72)													
1320F.1-1	58	4	0.1	0.28	2.246	0.043	0.1495	0.0038	2374	38	2340	43	-1
1320F.1-2	159	74	0.5	0.06	2.335	0.030	0.1471	0.0012	2298	25	2312	14	1
1320F.1-3	101	10	0.1	0.32	2.384	0.048	0.1471	0.0021	2258	38	2312	24	2
1320F.2-1	238	3	0.0	0.06	2.332	0.028	0.1445	0.0016	2300	23	2281	19	-1
1320F.2-2	192	66	0.3	-0.02	2.229	0.028	0.1462	0.0011	2390	25	2302	13	-4
1320F.2-3	61	206	3.4	0.47	2.363	0.041	0.1499	0.0027	2275	33	2345	31	3
1320F.3-1	67	70	1.0	0.73	2.278	0.036	0.1473	0.0026	2346	31	2315	31	-1
Xenotime older group (2097 ± 5 Ma, *n* = 12, MSWD = 0.59)													
1320F.1-1	1289	883	0.7	-0.03	2.565	0.049	0.1303	0.0006	2122	34	2102	8	-1
1320F.1-2	1025	517	0.5	-0.01	2.643	0.052	0.1296	0.0006	2069	35	2092	9	1
1320F.1-3	1439	818	0.6	0.03	2.606	0.050	0.1303	0.0006	2094	34	2103	8	1
1320F.1-4	938	437	0.5	0.02	2.675	0.063	0.1307	0.0012	2047	41	2107	16	3
1320F.1-5	1596	595	0.4	0.03	2.620	0.049	0.1300	0.0005	2084	33	2099	7	1
1320F.1-7	1748	990	0.6	0.01	2.598	0.048	0.1291	0.0005	2099	33	2085	7	-1
1320F.1-8	1867	1380	0.8	0.03	2.616	0.048	0.1300	0.0005	2087	33	2097	7	1
1320F.1-10	2639	2257	0.9	0.02	2.516	0.045	0.1297	0.0004	2157	33	2094	5	-4
1320F.1-11	1629	552	0.3	0.01	2.580	0.048	0.1300	0.0005	2112	33	2098	7	-1
1320F.1-12	1806	804	0.5	-0.01	2.647	0.048	0.1305	0.0005	2066	32	2104	6	2
1320F.1-13	2372	2567	1.1	0.01	2.530	0.046	0.1298	0.0005	2147	33	2095	6	-3
1320F.1-15	2840	2538	0.9	0.00	2.480	0.044	0.1297	0.0008	2184	33	2094	11	-5
Xenotime younger group (2052 ± 9 Ma, *n* = 3, MSWD = 0.27)													
1320F.1-6	1636	2694	1.7	0.05	2.565	0.048	0.1266	0.0005	2122	34	2051	7	-4
1320F.1-9	1902	694	0.4	0.01	2.630	0.048	0.1268	0.0005	2077	33	2054	7	-1
1320F.1-14	1827	892	0.5	0.06	2.589	0.049	0.1261	0.0009	2106	34	2044	12	-4

Table DR6. U-Pb data for monazite in ABDP9 (363.03–.22 m), Wittenoom Formation

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Ages (Ma) ^{238}U/^{206}Pb*	±	^{207}Pb*/^{206}Pb*	±	Disc. (%)
Older group (2289 ± 16 Ma, *n* = 11, MSWD = 1.4)													
1320A.1-1	119	1457	12	0.01	2.367	0.031	0.1467	0.0020	2272	25	2308	24	2
1320A.1-2	102	1069	10	0.02	2.530	0.052	0.1448	0.0016	2147	38	2285	19	6
1320A.1-3	93	1787	19	0.08	2.395	0.042	0.1417	0.0016	2249	33	2249	19	0
1320B.1-1	100	932	9.3	0.36	2.460	0.035	0.1439	0.0018	2199	26	2275	22	3
1320B.1-2	123	584	4.8	0.41	2.387	0.040	0.1457	0.0021	2256	32	2296	25	2
1320B.1-5	89	1551	17	0.34	2.439	0.044	0.1453	0.0020	2215	33	2291	24	3
1320B.1-6	140	345	2.5	0.04	2.477	0.051	0.1474	0.0013	2186	38	2316	15	6
1320D.2-1	108	669	6.2	0.51	2.406	0.034	0.1431	0.0018	2241	27	2265	22	1
1320J.1-1	123	922	7.5	0.15	2.403	0.049	0.1435	0.0014	2243	39	2270	17	1
1320J.1-2	103	2006	19	0.00	2.452	0.052	0.1477	0.0015	2205	39	2320	18	5
1320J.1-3	90	557	6.2	0.75	2.537	0.047	0.1457	0.0024	2142	34	2296	28	7
Younger group (2195 ± 21 Ma, *n* = 3, MSWD = 0.87)													
1320B.1-4	249	426	1.7	0.14	2.443	0.038	0.1367	0.0011	2212	29	2186	14	-1
1320D.1-1	96	454	4.7	0.18	2.499	0.036	0.1394	0.0017	2170	27	2219	22	2
1320J.1-4	121	792	6.6	0.02	2.423	0.057	0.1369	0.0024	2227	44	2188	30	-2

Table DR7. U-Pb data for monazite in DDH186 (183.0 m), Roy Hill Shale Member

Analysis No.	U (ppm)	Th (ppm)	Th/U	f_{206} (%)	^{204}Pb corrected ratios $^{238}U/^{206}Pb^*$	±	$^{207}Pb^*/^{206}Pb^*$	±	Ages (Ma) $^{238}U/^{206}Pb^*$	±	$^{207}Pb^*/^{206}Pb^*$	±	Disc. (%)
Main group (2407 ± 8 Ma, n = 21, MSWD = 0.67)													
1902D.1-1	116	345	3.0	0.07	2.108	0.059	0.1542	0.0021	2503	58	2393	23	-5
1902C.1-15	182	190	1.0	0.06	2.155	0.046	0.1538	0.0018	2457	43	2389	20	-3
1902C.1-10	643	231	0.4	0.18	2.161	0.039	0.1544	0.0017	2452	37	2396	19	-2
1902C.1-16	221	202	0.9	-0.08	2.162	0.040	0.1549	0.0015	2451	37	2400	17	-2
1902C.1-6	250	1207	4.8	0.06	2.165	0.047	0.1548	0.0014	2448	44	2399	16	-2
1902C.1-4	266	299	1.1	0.35	2.195	0.041	0.1529	0.0030	2420	38	2379	34	-2
1902D.1-3	214	1127	5.3	0.11	2.193	0.031	0.1535	0.0016	2422	29	2385	18	-2
1902C.1-14	212	116	0.5	0.18	2.183	0.040	0.1546	0.0019	2431	37	2397	21	-1
1902C.1-5	283	250	0.9	0.11	2.151	0.050	0.1577	0.0016	2461	48	2431	17	-1
1902C.1-7	393	225	0.6	0.17	2.189	0.052	0.1564	0.0016	2426	48	2417	18	0
1902C.1-1	225	635	2.8	-0.06	2.182	0.049	0.1574	0.0015	2432	46	2428	16	0
1902C.1-3	252	4125	16	0.13	2.187	0.042	0.1570	0.0016	2427	39	2424	18	0
1902C.1-13	164	16	0.1	0.19	2.201	0.046	0.1560	0.0020	2414	42	2413	22	0
1902D.1-2	57	739	13	-0.16	2.181	0.047	0.1583	0.0032	2433	43	2438	34	0
1902C.1-12	695	110	0.2	0.18	2.276	0.028	0.1538	0.0016	2348	24	2388	18	2
1902D.1-4	282	1032	3.7	0.09	2.251	0.030	0.1558	0.0014	2369	27	2411	16	2
1902D.1-5	52	148	2.8	0.18	2.272	0.055	0.1555	0.0036	2352	47	2407	39	2
1902D.1-6	125	339	2.7	-0.08	2.274	0.039	0.1561	0.0022	2349	33	2414	24	3
1902C.1-9	868	1989	2.3	0.05	2.061	0.036	0.1553	0.0009	2550	36	2405	10	-6
1902C.1-8	242	1407	5.8	0.03	2.356	0.046	0.1574	0.0017	2280	37	2428	18	6
1902C.1-11	679	226	0.3	0.10	2.427	0.044	0.1544	0.0015	2225	34	2395	16	7
Rejected													
1902C.1-2	63	5484	88	0.11	2.464	0.057	0.1745	0.0038	2196	43	2602	36	16