



Supplement of

Multiple growth of zirconolite in marble (Mogok metamorphic belt, Myanmar): evidence for episodes of fluid metasomatism and Zr–Ti–U mineralization in metacarbonate systems

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Supplement materials

Figure S1. Plots of Nb₂O₅ (a), HfO₂ (b), MgO (c), FeO (d), Al₂O₃(e), and ThO₂(f) with bars (data measured by EMPA) to discriminate Zrl-III from Zrl-I and Zrl-II.

Figure S2. Images of representative LA-ICP-MS analysis pits. Small pits (16 μm) and big pits (32 μm) were for dating and trace elements analyses, respectively. The numbers represent the ²⁰⁷Pb-corrected ²⁰⁶Pb/²³⁸U ages (Ma) or the Hf composition (ppm).

Table S1. Representative major and minor element compositions (wt%) of baddeleyite, rutile, geikielite, spinel, forsterite, and phlogopite.

Table S2. U–Pb data for different types of zirconolites from the MMB.

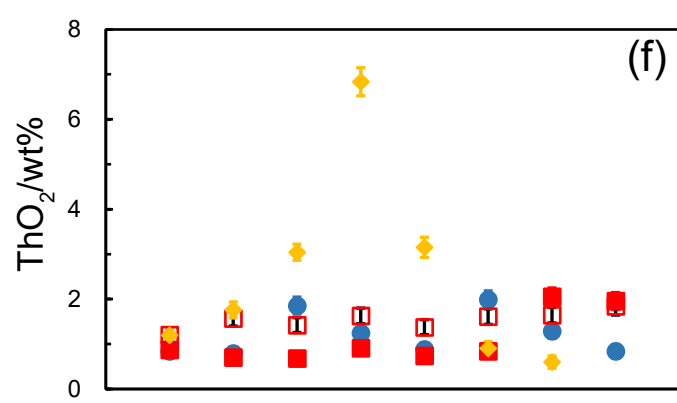
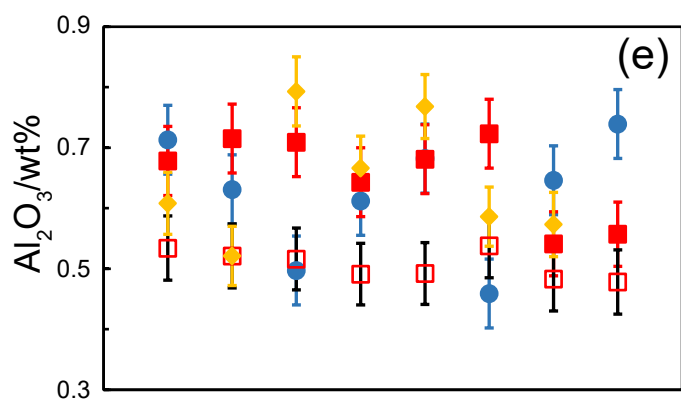
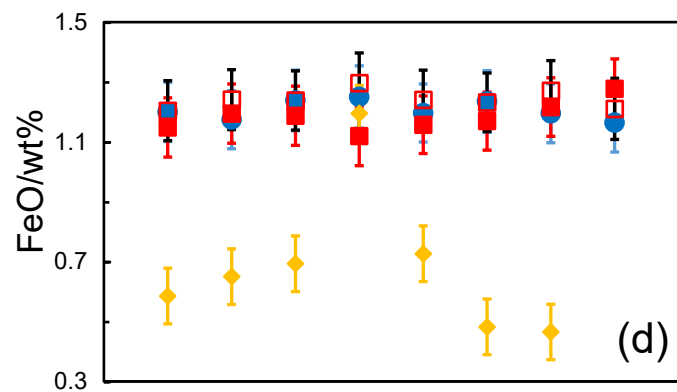
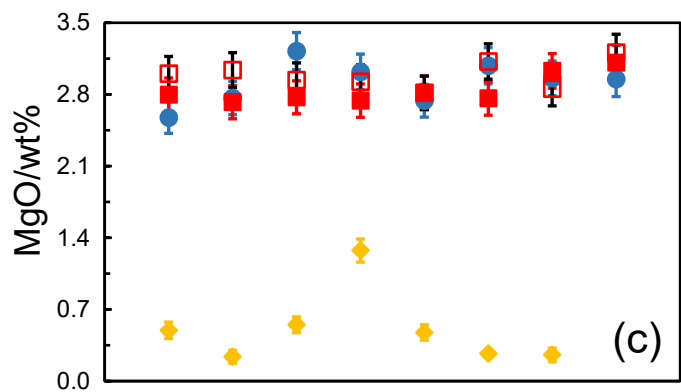
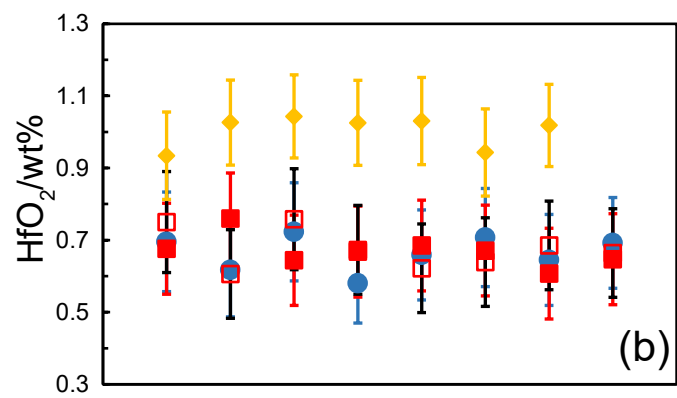
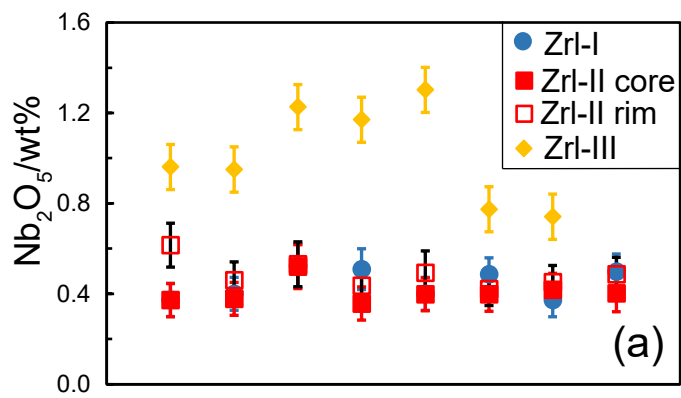


Figure S1

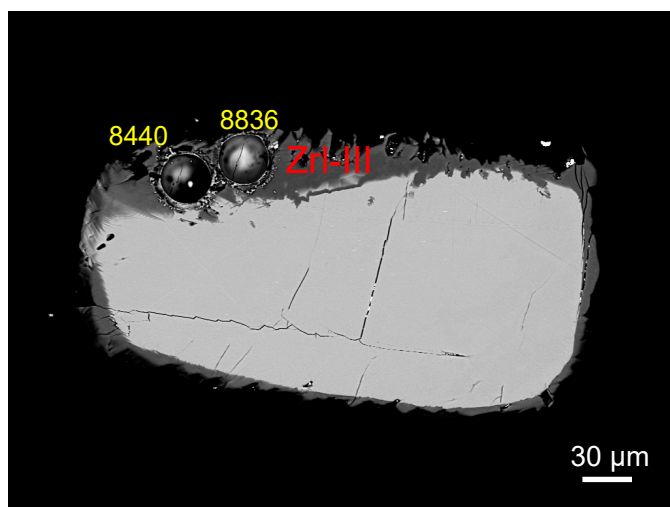
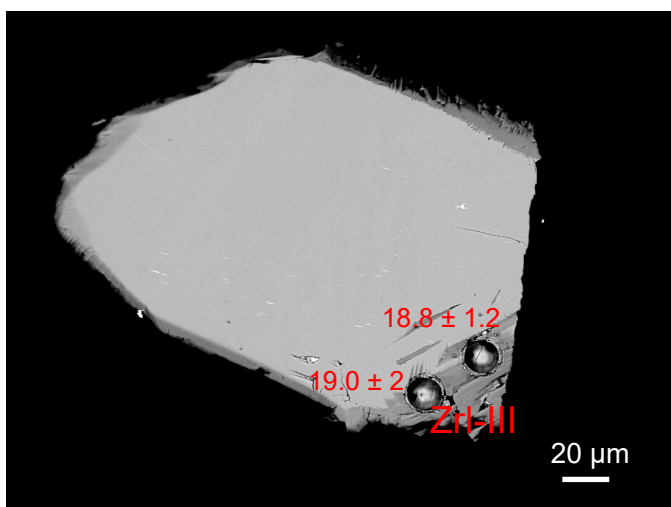
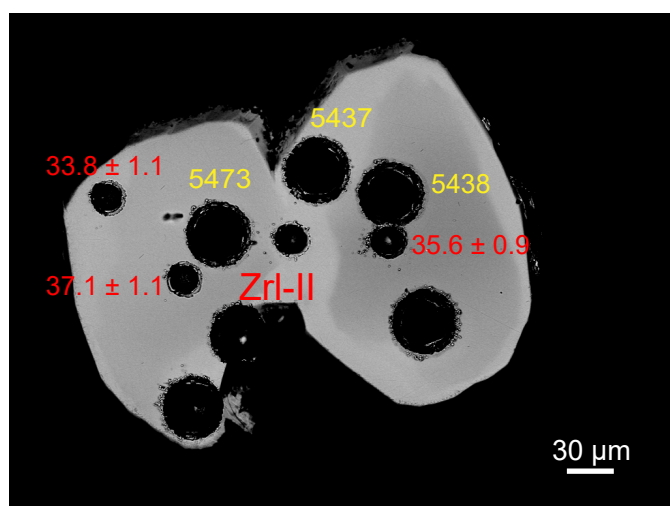
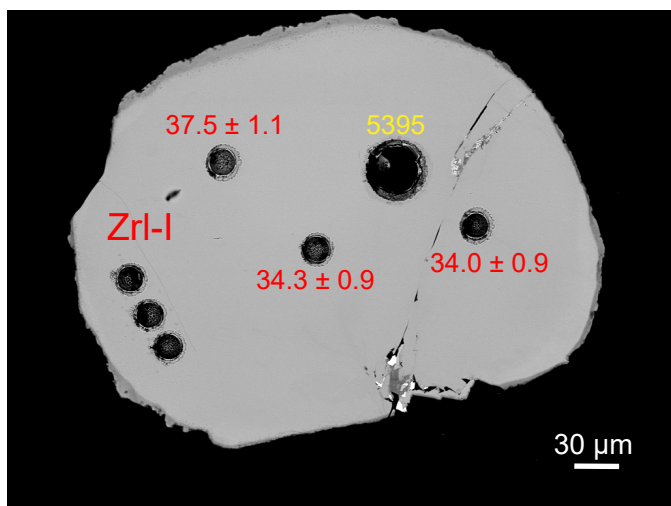


Figure S2

Table S1. Representative major and minor element compositions (wt%) of baddeleyite, rutile, geikielite, spinel, forsterite, and phlogopite.

Baddeleyite composition

Sample	13MDL76-A			13MDL76-B		
UO₂	bdl	bdl	0.23	bdl	bdl	bdl
ZrO₂	94.58	97.28	98.18	97.71	95.25	95.54
CaO	bdl	bdl	bdl	0.02	bdl	0.04
TiO₂	0.35	0.36	0.18	0.37	0.31	0.52
ThO₂	bdl	bdl	bdl	0.06	bdl	bdl
HfO₂	5.21	2.40	2.33	2.32	5.43	2.28
WO₃	bdl	bdl	bdl	bdl	bdl	bdl
SiO₂	bdl	bdl	bdl	bdl	bdl	bdl
MgO	0.02	0.02	0.03	0.03	0.03	0.02
Al₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
K₂O	bdl	bdl	bdl	bdl	bdl	bdl
Sc₂O₃	bdl	bdl	bdl	bdl	0.02	bdl
FeO	bdl	bdl	bdl	bdl	bdl	0.05
MnO	bdl	bdl	bdl	bdl	bdl	bdl
Nb₂O₅	0.13	0.22	0.17	0.13	0.15	0.09
La₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Ce₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Pr₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Nd₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Sm₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Eu₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Gd₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Dy₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Er₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Yb₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Y₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Total	100.3	100.3	101.1	100.6	101.2	98.5

Rutile composition

Sample	13MDL76-A			13MDL76-B		
UO ₂	bdl	bdl	bdl	bdl	bdl	bdl
ZrO ₂	0.29	0.03	0.15	0.03	0.59	0.21
CaO	0.07	0.82	0.52	1.10	0.19	0.74
TiO ₂	98.70	98.09	97.67	98.90	97.03	97.66
ThO ₂	bdl	bdl	bdl	bdl	bdl	bdl
HfO ₂	0.08	bdl	0.07	0.05	0.08	0.03
WO ₃	bdl	0.15	0.16	bdl	0.17	bdl
SiO ₂	0.06	0.08	bdl	0.03	0.04	0.05
MgO	0.06	0.07	0.02	0.03	0.03	bdl
Al ₂ O ₃	0.03	0.04	0.01	0.04	0.11	0.07
K ₂ O	0.17	0.11	0.01	0.09	0.09	0.02
Sc ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
FeO	0.02	0.05	0.09	0.03	0.09	0.07
MnO	bdl	bdl	bdl	bdl	bdl	bdl
Nb ₂ O ₅	0.10	0.08	0.06	bdl	0.54	0.30
La ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Ce ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Pr ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Nd ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Sm ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Eu ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Gd ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Dy ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Er ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Yb ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Y ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl
Total	99.6	99.5	98.8	100.3	99.0	99.2

Geikielite composition

Sample	13MDL76-A			13MDL76-B		
UO₂	bdl	bdl	bdl	bdl	bdl	bdl
ZrO₂	bdl	bdl	0.04	bdl	bdl	bdl
CaO	0.01	0.10	0.11	0.01	0.11	0.03
TiO₂	65.54	63.32	64.92	64.68	64.06	64.65
ThO₂	bdl	bdl	bdl	bdl	bdl	bdl
HfO₂	bdl	bdl	bdl	bdl	bdl	0.05
WO₃	bdl	bdl	bdl	bdl	bdl	bdl
SiO₂	bdl	bdl	bdl	bdl	0.03	bdl
MgO	27.43	28.79	30.00	28.72	28.60	29.84
Al₂O₃	0.02	bdl	bdl	0.02	bdl	bdl
K₂O	bdl	bdl	bdl	bdl	bdl	bdl
Sc₂O₃	bdl	bdl	bdl	bdl	bdl	0.01
FeO	7.02	7.00	5.31	5.42	5.31	5.23
MnO	0.04	0.06	0.05	0.06	0.02	0.03
Nb₂O₅	bdl	bdl	bdl	bdl	bdl	bdl
La₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Ce₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Pr₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Nd₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Sm₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Eu₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Gd₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Dy₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Er₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Yb₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Y₂O₃	bdl	bdl	bdl	bdl	bdl	bdl
Total	100.2	99.5	100.6	99.2	98.4	100.1

Spinel composition

Sample	13MDL76-A				13MDL76-B			
	Core		Rim		Core		Rim	
Texture								
SiO₂	bdl	bdl	bdl	bdl	bdl	bdl	0.03	bdl
TiO₂	0.24	0.27	0.15	0.08	0.24	0.25	0.10	0.11
Al₂O₃	68.80	68.53	69.09	69.07	68.02	68.22	69.73	70.10
Cr₂O₃	2.41	2.34	1.03	1.02	3.23	3.25	1.44	0.80
FeO	1.34	1.25	1.17	1.14	1.21	1.28	1.12	1.15
MnO	0.01	0.00	bdl	0.02	0.02	bdl	0.01	bdl
MgO	27.48	27.32	27.58	26.84	27.43	27.52	27.32	27.29
CaO	bdl	bdl	0.05	0.39	0.02	0.02	0.18	0.06
Na₂O	bdl	0.01	bdl	bdl	0.01	0.01	bdl	0.02
K₂O	bdl	bdl	bdl	0.01	bdl	bdl	0.01	bdl
NiO	bdl	0.02	0.01	0.01	bdl	bdl	bdl	0.01
Total	100.29	99.75	99.08	98.58	100.21	100.54	99.92	99.54
Si	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000
Ti	0.004	0.005	0.003	0.001	0.004	0.004	0.002	0.002
Al	1.942	1.944	1.962	1.974	1.926	1.925	1.968	1.981
Cr	0.046	0.045	0.020	0.020	0.061	0.062	0.027	0.015
Fe³⁺	0.004	0.002	0.013	0.004	0.003	0.005	0.000	0.000
Fe²⁺	0.023	0.023	0.011	0.019	0.022	0.021	0.022	0.023
Mn	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000
Mg	0.981	0.980	0.990	0.970	0.982	0.982	0.975	0.976
Ca	0.000	0.000	0.001	0.010	0.001	0.00	0.005	0.002
Na	0.000	0.001	0.000	0.000	0.00	0.001	0.000	0.001
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	3	3	3	3	3	3	3	3
Mg[#]	0.977	0.977	0.989	0.981	0.978	0.979	0.978	0.977

Mg[#] = Mg/(Mg+Fe²⁺)

Forsterite composition

Sample	13MDL76-A		13MDL76-B	
SiO₂	42.96	43.13	42.76	42.98
TiO₂	0.02	bdl	0.03	bdl
Al₂O₃	bdl	bdl	bdl	bdl
Cr₂O₃	0.03	0.02	bdl	bdl
FeO	0.43	0.93	0.90	0.89
MnO	0.01	0.01	0.01	bdl
MgO	57.29	56.61	56.94	57.22
CaO	0.02	0.10	0.08	0.06
Na₂O	0.01	bdl	0.01	bdl
K₂O	bdl	0.02	0.01	0.01
NiO	0.04	0.01	0.01	bdl
Total	100.80	100.82	100.76	101.17
Si	1.000	1.005	0.998	0.999
Ti	0.000	0.000	0.001	0.000
Al	0.000	0.000	0.000	0.000
Cr	0.001	0.000	0.000	0.000
Fe²⁺	0.008	0.018	0.018	0.017
Mn	0.000	0.000	0.000	0.000
Mg	1.988	1.967	1.982	1.983
Ca	0.000	0.002	0.002	0.002
Na	0.000	0.000	0.000	0.000
K	0.000	0.001	0.000	0.000
Ni	0.001	0.000	0.000	0.000
Total	2.999	2.995	3.001	3.001
Mg#	0.996	0.991	0.991	0.992

Phlogopite composition

Sample	13MDL76-A				13MDL76-B			
	Core		Rim		Core		Rim	
Texture								
SiO₂	41.34	41.38	40.39	40.95	41.20	41.31	40.44	40.68
TiO₂	1.44	1.21	1.54	1.32	1.18	1.15	0.61	0.57
Al₂O₃	15.73	15.91	16.14	16.11	15.79	16.01	16.23	16.35
Cr₂O₃	0.05	0.04	0.01	0.04	0.03	0.02	0.01	0.01
FeO	0.23	0.20	0.28	0.18	0.24	0.23	0.14	0.11
MnO	0.02	0.01	0.02	0.01	bdl	0.02	0.01	0.01
MgO	27.03	27.15	26.95	27.60	26.53	26.73	26.89	26.84
CaO	0.01	0.01	0.03	0.03	0.01	0.01	0.02	0.03
Na₂O	2.29	2.23	2.35	2.82	2.17	1.89	0.78	0.73
K₂O	7.25	7.17	7.24	6.15	7.83	7.90	9.81	9.83
NiO	bdl	bdl	bdl	bdl	bdl	0.01	0.03	0.01
F	1.79	1.77	1.59	1.88	1.57	1.66	1.74	1.88
Cl	0.01	0.02	0.02	0.02	0.03	0.02	0.01	0.02
Total	97.18	97.09	96.54	97.08	96.55	96.93	96.71	97.06
Si	2.841	2.842	2.794	2.808	2.851	2.847	2.820	2.827
Ti	0.074	0.063	0.080	0.068	0.061	0.060	0.032	0.030
Al^{IV}	1.159	1.158	1.206	1.192	1.149	1.153	1.180	1.173
Al^{VI}	0.115	0.130	0.110	0.110	0.138	0.147	0.153	0.167
Cr	0.003	0.002	0.001	0.002	0.002	0.001	0.001	0.001
Fe	0.013	0.011	0.016	0.010	0.014	0.013	0.008	0.006
Mn	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001
Mg	2.769	2.780	2.780	2.821	2.736	2.746	2.795	2.781
Ca	0.001	0.001	0.002	0.002	0.001	0.000	0.001	0.002
Na	0.305	0.297	0.315	0.375	0.291	0.253	0.105	0.098
K	0.636	0.628	0.639	0.538	0.691	0.695	0.873	0.872
Ni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg#	0.995	0.996	0.994	0.996	0.995	0.995	0.997	0.998

bdl: below detection limits.

Table S2. U-Pb data for different types of zirconolite from the MMB.

Samples	Pb	Th	U	Th/U	$^{238}\text{U}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	f_{206}	^{207}Pb -corrected date	
										$^{206}\text{Pb}/^{238}\text{U}$	1 σ
Zirconolite-I from 13MDL76-A											
13MDL76-A-Zr-I-1	1499	12673	231568	0.05	169	4.9	0.0550	0.0017	0.010	37.5	1.1
13MDL76-A-Zr-I-2	947	17309	231483	0.07	184	5.1	0.0598	0.0010	0.016	34.3	0.9
13MDL76-A-Zr-I-3	1125	17693	271355	0.07	186	4.8	0.0592	0.0010	0.016	34.0	0.9
13MDL76-A-Zr-I-4	1127	8705	203995	0.04	176	5.0	0.0619	0.0016	0.019	35.7	1.0
13MDL76-A-Zr-I-5	1214	8566	203147	0.04	179	5.1	0.0601	0.0018	0.017	35.4	1.0
13MDL76-A-Zr-I-6	1198	11006	219229	0.05	178	4.8	0.0602	0.0011	0.017	35.5	0.9
13MDL76-A-Zr-I-7	1201	11972	225215	0.05	181	4.9	0.0592	0.0011	0.016	35.0	0.9
13MDL76-A-Zr-I-8	788	6514	175695	0.04	176	6.2	0.0533	0.0018	0.008	36.1	1.3
13MDL76-A-Zr-I-9	913	10167	179629	0.06	172	6.2	0.0536	0.0021	0.009	37.2	1.3
13MDL76-A-Zr-I-10	981	8126	176706	0.05	169	5.7	0.0563	0.0021	0.012	37.7	1.3
13MDL76-A-Zr-I-11	1107	9875	212117	0.05	180	5.5	0.0570	0.0011	0.013	35.3	1.1
13MDL76-A-Zr-I-12	1266	11717	229719	0.05	186	5.9	0.0544	0.0015	0.010	34.3	1.1
13MDL76-A-Zr-I-13	1179	12649	248471	0.05	190	5.8	0.0562	0.0014	0.012	33.5	1.0
13MDL76-A-Zr-I-14	1210	14477	243349	0.06	185	5.8	0.0560	0.0014	0.012	34.3	1.1
13MDL76-A-Zr-I-15	1063	17580	224662	0.08	185	5.8	0.0560	0.0017	0.012	34.4	1.1
13MDL76-A-Zr-I-16	1129	19205	263716	0.07	189	5.7	0.0581	0.0014	0.014	33.5	1.0
13MDL76-A-Zr-I-17	1156	17592	285222	0.06	190	5.4	0.0566	0.0011	0.013	33.3	1.0
13MDL76-A-Zr-I-18	1024	17791	263610	0.07	190	5.4	0.0567	0.0011	0.013	33.3	1.0
Zirconolite-I from 13MDL76-B											
13MDL76-B-Zr-I-1	1121	12583	246457	0.05	186	5.2	0.0586	0.0012	0.015	34.1	1.0
13MDL76-B-Zr-I-2	1037	14791	232460	0.06	191	5.5	0.0572	0.0011	0.013	33.2	1.0
13MDL76-B-Zr-I-3	1095	15920	241874	0.07	183	5.4	0.0573	0.0012	0.013	34.6	1.0
13MDL76-B-Zr-I-4	1204	13436	260313	0.05	184	5.4	0.0564	0.0013	0.012	34.5	1.0
13MDL76-B-Zr-I-5	1022	15382	238978	0.06	178	5.1	0.0583	0.0012	0.015	35.5	1.0
13MDL76-B-Zr-I-6	1080	18318	239078	0.08	186	5.2	0.0564	0.0012	0.012	34.1	1.0
13MDL76-B-Zr-I-7	1154	7263	207805	0.03	168	5.9	0.0565	0.0021	0.012	37.9	1.3

13MDL76-B-ZrI-I-8	1080	7853	186290	0.04	168	6.5	0.0546	0.0029	0.010	37.9	1.5	3.9
13MDL76-B-ZrI-I-9	1206	7488	202458	0.04	169	6.0	0.0562	0.0025	0.012	37.6	1.3	3.6
13MDL76-B-ZrI-I-10	1355	10958	224193	0.05	171	5.6	0.0575	0.0017	0.014	37.0	1.2	3.3
13MDL76-B-ZrI-I-11	1233	6971	204623	0.03	167	5.6	0.0583	0.0020	0.015	37.9	1.3	3.4
13MDL76-B-ZrI-I-12	1195	12920	232836	0.06	189	6.1	0.0545	0.0012	0.010	33.7	1.1	3.2
13MDL76-B-ZrI-I-13	1220	9886	223721	0.04	181	5.9	0.0553	0.0017	0.011	35.2	1.1	3.3
13MDL76-B-ZrI-I-14	1507	12839	250330	0.05	183	5.0	0.0570	0.0013	0.013	34.7	1.0	2.7
13MDL76-B-ZrI-I-15	1063	8878	177873	0.05	176	5.0	0.0563	0.0013	0.012	36.0	1.0	2.8
13MDL76-B-ZrI-I-16	1120	7314	208529	0.04	182	5.0	0.0569	0.0013	0.013	34.9	1.0	2.7

Zirconlite-II from 13MDL76-A

13MDL76-A-ZrI II-1(C)	1043	17637	234080	0.08	186	5.5	0.0570	0.0011	0.013	34.1	1.0	3.0
13MDL76-A-ZrI II-2(C)	1202	15225	279749	0.05	182	5.3	0.0575	0.0010	0.014	34.9	1.0	2.9
13MDL76-A-ZrI II-3(R)	1169	13948	270951	0.05	184	5.4	0.0582	0.0010	0.015	34.4	1.0	2.9
13MDL76-A-ZrI II-4(R)	1104	16515	250711	0.07	186	5.5	0.0568	0.0010	0.013	34.1	1.0	3.0

Zirconlite-II from 13MDL76-B

13MDL76-B-ZrI II-1(R)	1237	9106	206245	0.04	189	6.4	0.0537	0.0016	0.009	33.7	1.2	3.4
13MDL76-B-ZrI II-2(R)	747	7202	171728	0.04	181	4.9	0.0581	0.0011	0.014	35.0	1.0	2.7
13MDL76-B-ZrI II-3(C)	1035	8338	205570	0.04	182	5.0	0.0593	0.0011	0.016	34.7	0.9	2.7
13MDL76-B-ZrI II-4(R)	1183	19046	236005	0.08	188	6.0	0.0581	0.0016	0.014	33.8	1.1	3.2
13MDL76-B-ZrI II-5(C)	1321	7821	217256	0.04	171	5.0	0.0565	0.0015	0.012	37.1	1.1	2.9
13MDL76-B-ZrI II-6(C)	1154	15122	240847	0.06	178	5.1	0.0568	0.0014	0.013	35.6	1.0	2.9
13MDL76-B-ZrI II-7(C)	1106	8616	215264	0.04	185	5.8	0.0579	0.0019	0.014	34.3	1.1	3.1

Zirconlite-III from 13MDL76-B

13MDL76-B-ZrI III-1	31	9715	8837	1.10	366	32.2	0.1023	0.0180	0.071	16.3	1.5	9.1
13MDL76-B-ZrI III-2	33	8735	8996	0.97	340	22.0	0.0924	0.0131	0.058	17.8	1.2	6.7
13MDL76-B-ZrI III-3	356	122130	42621	2.87	328	33.3	0.0728	0.0180	0.033	19.0	2.0	10.4
13MDL76-B-ZrI III-4	38	23772	8135	2.92	327	21.4	0.0961	0.0121	0.063	18.5	1.2	6.7
13MDL76-B-ZrI III-5	105	15323	35237	0.43	334	13.4	0.0649	0.0050	0.023	18.8	0.8	4.1
13MDL76-B-ZrI III-6	148	18021	44590	0.40	312	15.5	0.0743	0.0078	0.035	19.9	1.0	5.1

C:core; R: rim.