

韩国太白山盆地古生界砂岩碎屑锆石 U-Pb 年代及其区域构造含义*

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Abstract The Tabeaksan basin is situated between the Kyonggi and Yongnam blocks, central-eastern Korea. Two samples were respectively sampled from the Lower Cambrian and Middle-Upper Carboniferous (Lower Permian?) sandstone layers of the basin, which detrital zircon U-Pb ages were measured by the LA-ICP-MS method. The sample 03TB01, 27 age data, records three reliable tectonic-thermal events in 1820 ~ 1945Ma, 2172 ~ 2195Ma and 2473 ~ 2593Ma, with relative probability peak ages of 1897Ma, 2177Ma and 2528Ma. The sample 03TB09, 47 age data, records five reliable tectonic-thermal events in 288 ~ 340Ma, 461 ~ 474Ma, 1780 ~ 1892Ma, 1941 ~ 1959Ma and 2012 ~ 2050Ma, in which most ages fall into two events with relative probability peak ages of 305Ma, 1867Ma. It was found that one similar tectonic-thermal event about 1850Ma all occurred in the Tabeaksan basin and the Kyonggi and Yongnam blocks, with lack of Neoprotozoic zircon ages distinct to the South China block. Based on the published depositional paleocurrent and paleogeographic framework of Lower Cambrian and Middle-Upper Carboniferous (Lower Permian?) for the Tabeaksan basin and its adjacent area, this research presents that close detrital provenance relationship existed between the Tabeaksan basin and Yongnam block at least during those periods of time, which tectonic attribute can be compared with the North China craton. On the other hand, though the Middle-Upper Carboniferous (Lower Permian?) sample records zircon U-Pb peak ages of 305Ma and 468Ma, probably related to tectonic-thermal events occurred in south margin of the united North China-Korea block, no detrital provenances supplied the Tabeaksan basin at least before Late Carboniferous (Early Permian?) due to few Neoprotozoic tectonic-thermal events recorded in detrital zircons of the two samples mentioned above.

Key words Detrital zircon; U-Pb ages; Tectonic-thermal event; Tabeaksan basin; Korea; North China

摘要 韩国中东部的太白山盆地位于京畿、岭南两个构造单元之间。采用 LA-ICP-MS 方法,从太白山盆地寒武统、中-上石炭统(下二叠统?)砂岩碎屑锆石中分别获得 27 个和 47 个 U-Pb 有效年龄,前者记录了 1820 ~ 1945Ma、2172 ~ 2195Ma、2473 ~ 2593Ma 等 3 期可信的构造热事件,相对概率峰值分别为 1897Ma、2177Ma 以及 2528Ma;后者记录了 288 ~ 340Ma、461 ~ 474Ma、1780 ~ 1892Ma、1941 ~ 1959Ma、2012 ~ 2050Ma 等 5 期可信的构造热事件,其中相对概率峰值为 305Ma 和 1867Ma 的两组年龄比较集中。研究认为,太白山盆地与京畿、岭南两个地块均发育大约 1850Ma 的构造热事件,缺乏华南比较特征的新元古代构造热事件;进一步依据太白山盆地相应时段沉积古流向和古地理分布,说明太白山盆地至少与岭南地块之间存在密切的碎屑物源和构造属性关系,其构造热事件记录可与华北克拉通对比。另一方面,尽管中-上石炭统(下二叠统?)碎屑锆石记录了峰值为 305Ma 和 468Ma 可能发生在华北-朝鲜联合块体南缘的俯冲或构造热事件,但上述两个样品的碎屑锆石均缺乏新元古代构造热事件的年龄记录,所以亲华南的陆块至少在晚石炭世(早二叠世?)以前并未向太白山盆地提供碎屑物源。

关键词 碎屑锆石; U-Pb 年代; 构造热事件; 太白山盆地; 韩国; 华北

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1 引言

大别-苏鲁构造带向东的延伸,或者说朝鲜半岛的大地构造划分及其与华北、华南块体的对比问题,这是近十余年来东亚大地构造及相关地质学研究的焦点问题之一(任纪舜, 1994; Chough *et al.*, 2000; 马文璞等, 2003; Li *et al.*, 2003; Oh, 2006)。对此,以往各国学者依据各自不同的实际材料提出了不同的解释模式(Cho *et al.*, 1995; Cho, 2001; Chang, 1996; Zhang, 1997; Cluzel, 1991; Cluzel *et al.*, 1991a, b; Yin and Nie, 1993, 1996; Chang and Park, 2001; Ishiwatari and Tsujimori, 2001; Tsujimori, 2002; Tsujimori *et al.*, 2006; Oh *et al.*, 2005, 2006; 郝天姚等, 2002),其中如下两种认识影响较大。其一,沉积-地层学研究强调北朝鲜平南盆地、南朝鲜湖南剪切带以东太白盆地地层(Duwibong Unit)与华北古生界及其古生物的可比性,而南朝鲜湖南剪切带以西的沃川盆地地层(Yeongweol Unit)则与华南的古生界可比(Kobayashi, 1967; Lee, 1980),因此提出并赞同大别-苏鲁-临津江-沃川带说;其二,另一些资料则支持中朝统一构造单元的观点(Kim and Lee, 1999, 2000; Jeong and Lee, 2000, 2004; Choi *et al.*, 2003; Kwon *et al.*, 2006),其主要依据是湖南剪切带两侧的Duwibong和Yeongweol单元不仅(层序)地层、古生物可以对比,而且沉积地球化学资料(如牙形石铋同位素)也可以对比,即临津江带和沃川带都不具有构造分隔意义。后一认识目前面临的最大挑战就是来自“沃川带”以北洪松地区高压榴辉岩带的发现(Oh *et al.*, 2004a, 2005)。

碎屑锆石微区 U-Pb 年代学信息在追溯、对比构造单元及其演化历史方面已经显示出很高的研究价值(Dickinson and Gehrels, 2003; Thomas *et al.*, 2004; Yue *et al.*, 2005; Najman, 2006)。借鉴该分析方法,本文针对南朝鲜太白盆地古生界的两个砂岩样品开展了研究,对碎屑锆石年代学反映的大地构造单元属性及其与中朝构造块体对比的有关问题提出了新的信息。

2 构造—沉积地质背景

前人对朝鲜半岛前寒武变质基底一般多持三分观点(Chough *et al.*, 2000),即自北而南由朗玲(Nangrim)地块,京畿(Kyonggi)地块和岭南(Yongnam)地块三大构造单元构成,其间分别被临津江和沃川两个晚古生代—中生代变质变形带(Cho *et al.*, 1995; Ree *et al.*, 1996; Cluzel *et al.*, 1991b; Oh *et al.*, 2004b)分割(图 1a)。尽管上述地块的变质构造演化和岩石构成各有特色,但一般下部均由新太古代—古元古代高级片麻岩和片岩、上部(上地壳)由中-新元古代片岩、石英岩、大理岩、钙硅质岩和角闪岩组成,都经历过角闪岩到麻粒岩相变质作用,并受到后期中生代较强的岩

浆侵入和构造叠加改造。而在两个晚古生代—中生代变质变形带中则保留了相对完整的古生代地层层序,也存在类似的构造叠加改造迹象。当然,随着研究(如变质岩石学和年代学)的深入,越来越多的资料显示朝鲜半岛的构造单元及其与中国的对比需要重新认识(如前言所述);特别是洪松地区高压榴辉岩带的发现,目前对朝鲜半岛前寒武变质基底已出现“两分”的倾向性认识,即提出原来的“京畿地块”实际是岭南与朗玲地块之间的晚古生代—三叠纪碰撞造山带(Oh *et al.*, 2006; Chough, 2006)。

太白山(Taebaeksan)盆地位于韩国东北部,湖南剪切带以东,并介于京畿、岭南两个构造单元之间(图 1b)。对于太白盆地的构造单元,其究竟是发育于沃川带元古代裂陷槽之上,还是归属岭南地块,迄今并无统一认识(Cluzel *et al.*, 1991a; Chang, 1996; Chough *et al.*, 2000)。湖南剪切带主要表现为一系列向东逆冲的断层,并强烈切割太白盆地的古生界和下中生界(图 1b)。根据韩国学者的研究(Kim and Turek, 1996; Cho *et al.*, 1999; Oh *et al.*, 2004b; Cheong *et al.*, 2006),湖南断层早-中侏罗世曾发育大规模的剪切活动。

太白山盆地主要发育古生界和下中生界,与下伏前寒武纪花岗岩、片麻岩和副变质岩呈不整合接触。一般认为该古生界由下寒武统一中奥陶统、中石炭统一二叠系构成,中奥陶统和中石炭统之间以角度不整合接触(Cheong, 1969; Reedman and Um, 1975; Chough *et al.*, 2000);但也有认为该区存在志留系,其与石炭系之间存在角度不整合(Lee, 1980)。基于实地考察,本文采用前一种观点。如图 2 所示,太白盆地下古生界主要为一套海相碳酸盐岩夹灰色、深灰色泥岩及砂岩和砂质砾岩,而上古生界(自下而上)分别产出中-上石炭统海陆交互相灰色碎屑岩夹煤层和灰岩层、二叠系陆相灰色、绿灰色砂岩和泥岩。此外,该区中生界主要由陆相浅灰色、杂色碎屑岩、火山熔岩—火山碎屑岩构成,其内部可能发育多个不整合界面,而中生界与下伏古生界也呈角度不整合接触。

3 样品位置、属性和前处理

考察剖面位于太白山盆地东南部,本文重点研究的两个砂岩样品(03TB01, 03TB09)分别取自下寒武统 Jangsan 组(Samcheog 群底部)和中-上石炭统(下二叠统?) Manhang 组(Pyeongang 群底部)(图 2),地理坐标分别为 N37°04'57.8", E129°03'14.2"; N37°05'38.0", E129°02'29.1"。Jangsan 组由灰色、粉红色砾质石英岩、石英砂岩组成,中厚层状,显示滨海和内陆架沉积特征,古地理分析显示其物源主要来自东部(Kwon *et al.*, 2006),厚度约 40~300m;Manhang 组主要为厚层状灰色砂岩夹泥岩,显示河流—三角洲沉积特征,古地理分析显示其物源主要来自东北部(Lee and Chough, 2006),厚度约 250~300m。两个样品均为中粒长石石英砂岩,分选中

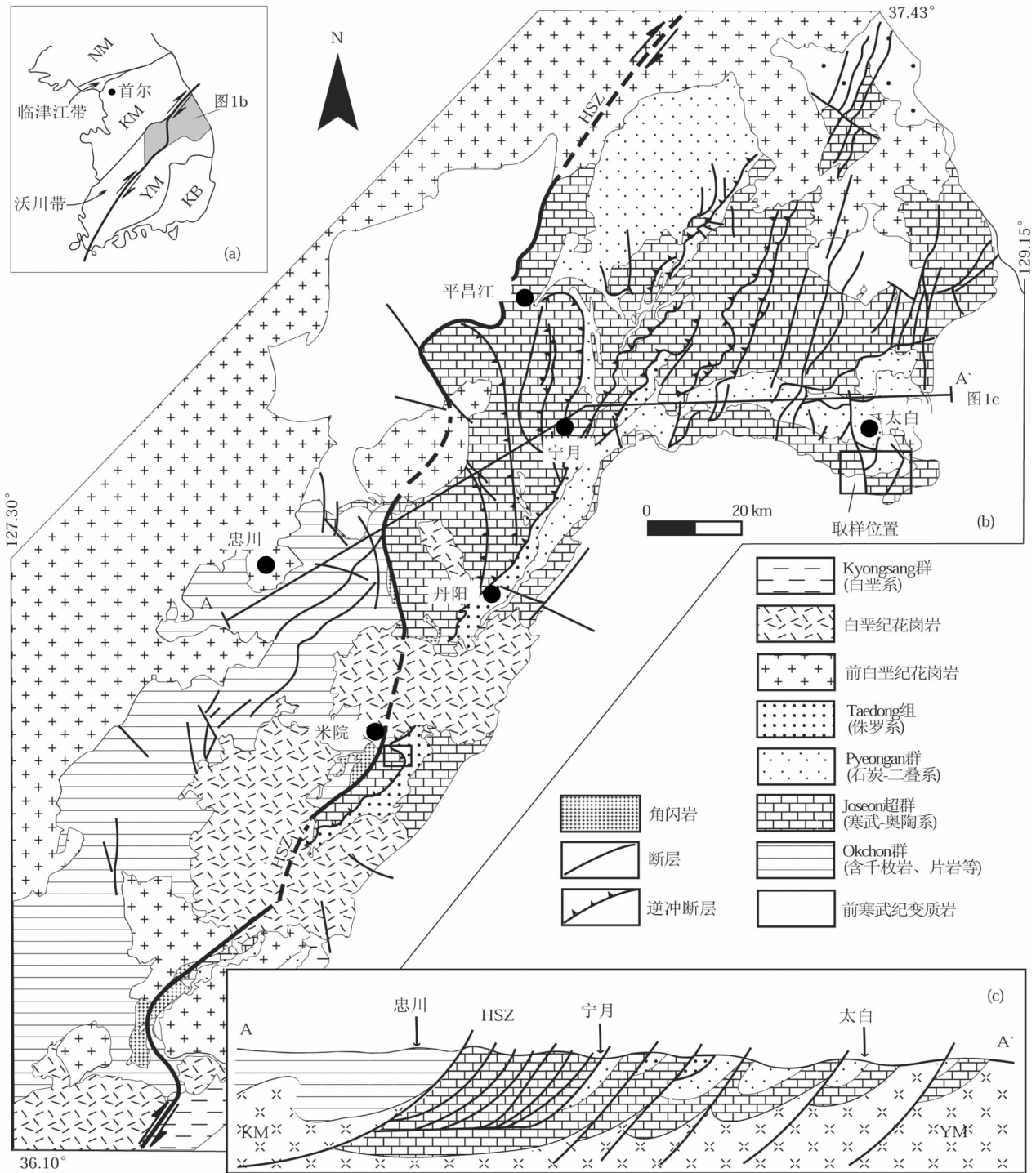


图1 朝鲜半岛大地构造单元(a)与太白山地区地质简化图(b)及构造剖面图(c)(据 Chough *et al.*, 2000, 修改)

图中缩写字母含义: NM-朗岭地块, KM-京畿地块, YM-岭南地块, KB-Kyeongsang 盆地, HSZ-湖南剪切带

Fig. 1 A schematic map (a) showing tectonic units of the Korea peninsula, with the geological map (b) and structural section (c) of the studied Tabeaksan area (modified from Chough *et al.*, 2000)

等,其中样品 O3TB01 中次圆、次棱角状颗粒居多,而样品 O3TB09 以次圆为主。因此,所选样品沉积时所包含的物源应该来自比较大的流域范围,受局部物源控制的可能性可以忽略,即样品能够反映大地构造单元演化的信息。

每个样品约 2~3kg,主要前处理程序为:① 首先经无污染机械粉碎至 10 目(最大岩块粒径约 2mm),然后利用标准干筛筛选 40~80 目,约 0.45~0.18mm 粒级;② 通过重液、精淘分离和电磁分离出电磁、无磁和强磁三部分重矿物;③

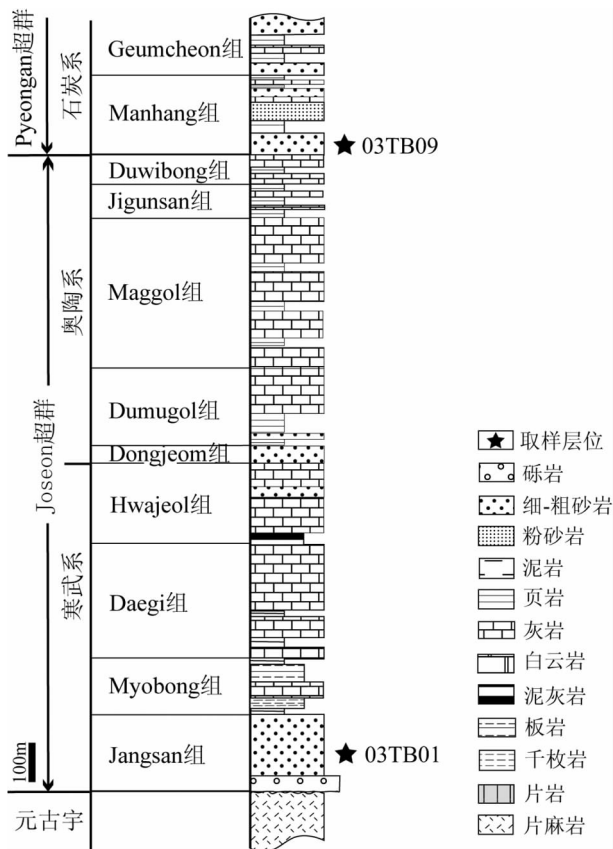


图2 太白山盆地古生代地层序列(据 Kim *et al.*, 2001, 修改)与样品采集层位

Fig. 2 The Paleozoic stratigraphic sequence of the Taebaek basin, in which the sampling layers and sample codes are marked(after Kim *et al.*, 2001)

通过双目镜从无磁部分中鉴定分离出碎屑锆石矿物;④镜下挑选干净清晰、结晶完好的、单成因的、蜕晶化程度低的锆石备用。

锆石样品靶的制备方法为:①首先将双面胶粘在玻璃片上,将锆石放置在双面胶上,然后在 Teflon 模具上用环氧树脂将其固化成圆饼;②用不同型号的砂纸和磨料将锆石磨去 1/3,然后将表面抛光,并用 Milli-Q 水清洗风干。

4 分析方法和数据处理

首先进行阴极发光(CL)分析,以确定锆石颗粒的内部结构,并提供相关成因信息。锆石阴极发光图像在中国科学院地质与地球物理研究所的 CAMECA 电子探针仪器上完成,分析电压为 50kV,电流为 15nA。

锆石 U-Pb 年龄测定在西北大学大陆动力学国家重点实验室激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS)上完成。激光剥蚀系统(LA)为德国 MicroLas 公司生产的 GeoLas200M,电感耦合等离子体质谱仪为 Hewlett Packard 公

司最新一代带有 Shield Torch 的 Agilent7500a ICP-MS。样品分析时激光斑束直径为 30 μ m,激光剥蚀样品的深度为 20 ~ 40 μ m。实验中采用 He 作为剥蚀物质的载气。用美标准参考物质 NIST SRM610 进行仪器最佳化,使仪器达到最大的灵敏度、最小的氧化物产率、最低的背景值和稳定的信号。采样方式为单点剥蚀,信号采集选用快速跳峰方式(Peak jumping),接收质量峰有²⁰²Hg、²⁰⁴Pb(²⁰⁴Hg)、²⁰⁶Pb、²⁰⁷Pb 和 ²³⁸U。一般每个样品选取约 70 ~ 80 颗锆石(点)采集数据。

锆石的 U-Pb 定年计算采用国际标准锆石 91500 做为外标,微量元素的浓度,采用美国国家标准物质局人工合成硅酸盐玻璃 NIST SRM610 做为外标,²⁹Si 做为内标进行计算(Yuan *et al.*, 2004; Jackson *et al.*, 2004)。数据处理采用软件 Glitter4.0,并应用 Andersen(2002)介绍的方法对 Pb 同位素组成进行普通 Pb 校正。对于碎屑锆石年龄大于 1000Ma 的样品,由于大量放射性成因 Pb 的存在因而采用²⁰⁷Pb/²⁰⁶Pb 表面年龄,而对于小于 1000 Ma 的样品,由于可用于测量的放射性成因 Pb 含量较低和普通 Pb 校正的不确定性,因而采用更为可靠的²⁰⁶Pb/²³⁸U 表面年龄(Sircombe, 1999)。

以不谐和度 10% 为标准遴选 U-Pb 年龄数据。表 1、2 列出了不谐和度小于或等于 10% 的样品数据,其中样品 03TB01 有效数据为 27 组,03TB09 有效数据点为 47 组。

5 年龄数据分析与结构

5.1 下寒武统样品 03TB01

在样品 03TB01 的 27 个碎屑锆石 U-Pb 有效年龄中(表 1),8 个不谐和度小于 5% (占 29.6%),其谐和曲线见图 3a。从年龄谱图上看(图 3b),U-Pb 有效年龄主要集中在 1820 ~ 1945Ma,2172 ~ 2195Ma,2473 ~ 2593Ma 等 3 个区间。

1820 ~ 1945Ma 区间共有 16 个碎屑锆石 U-Pb 年龄,占总有效数据的 59.3%,其算术平均值约为 1882Ma,而相对概率峰值为 1897Ma(图 3b)。该组年龄数据的不谐和度分布于 1% ~ 10%,是主要的和可信的年龄分布区间。在 16 颗碎屑锆石中,约 69% 的 Th/U 比值大于 0.4,只有约 6% 的 Th/U 比值小于 0.1(表 1);结合 CL 图揭示的颗粒形态和内部结构分析(图 4),认为这组碎屑锆石中以岩浆成因为主;但约 19% 的碎屑锆石仍然显示出交代或重结晶的成因属性,并具有弱分带或云雾状分带、海绵状分带等特征。

2172 ~ 2195Ma 区间共有 3 个碎屑锆石 U-Pb 年龄,占总有效数据的 11.1%,其算术平均值约为 2182Ma,而相对概率峰值为 2177Ma(图 3b)。该区间年龄的不谐和度为 -1% ~ 9%,平均 5.0%。在这 3 颗碎屑锆石中,2195Ma 锆石的 Th/U 比值为 0.28(表 1),结合 CL 图分析认为属变质成因(图 4);剩余均显示出特征的柱状和/或较清晰的内部分带特征,应属岩浆成因。

2473 ~ 2593Ma 区间共有 3 个碎屑锆石 U-Pb 年龄,占总有效数据的 11.1%,其算术平均值约为 2528Ma,没有明显的

表1 下寒武统 Jangsan 组砂岩样品(03TB01)碎屑锆石 U-Pb 年龄测定结果

Table 1 U-Pb dating data of sandstone detrital zircons (sample no. 03TB01) from the Jangsan Formation, Lower Cambrian

点号	U ($\times 10^{-6}$)	Pb ($\times 10^{-6}$)	Th/U	同位素比值			表面年龄(Ma)			不谐和度
				$^{207}\text{Pb}/^{206}\text{Pb}$ ($\pm 1\sigma$)	$^{207}\text{Pb}/^{235}\text{U}$ ($\pm 1\sigma$)	$^{206}\text{Pb}/^{238}\text{U}$ ($\pm 1\sigma$)	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	
01	223.28	348.34	0.68	0.11834 \pm 0.00124	5.39421 \pm 0.03507	0.33052 \pm 0.00191	1931 \pm 5	1884 \pm 6	1841 \pm 9	2%
03	346.78	622.64	0.21	0.12215 \pm 0.00126	6.73402 \pm 0.04149	0.39976 \pm 0.00228	1988 \pm 5	2077 \pm 5	2168 \pm 11	-4%
08	263.44	403.69	0.53	0.11895 \pm 0.00126	5.33637 \pm 0.03569	0.32531 \pm 0.00189	1941 \pm 5	1875 \pm 6	1816 \pm 9	3%
09	313.07	391.10	0.25	0.11405 \pm 0.00122	4.32941 \pm 0.02931	0.27525 \pm 0.00159	1865 \pm 5	1699 \pm 6	1567 \pm 8	8%
10	274.46	362.90	0.28	0.1151 \pm 0.00121	4.56912 \pm 0.0298	0.28785 \pm 0.00165	1881 \pm 5	1744 \pm 5	1631 \pm 8	7%
16	34.56	54.97	0.59	0.11131 \pm 0.00183	4.90062 \pm 0.07217	0.3193 \pm 0.00233	1821 \pm 31	1802 \pm 12	1786 \pm 11	1%
19	330.65	410.89	0.14	0.11407 \pm 0.00103	4.10876 \pm 0.02903	0.26125 \pm 0.00148	1865 \pm 17	1656 \pm 6	1496 \pm 8	10%
22	271.35	397.59	0.57	0.12463 \pm 0.0013	5.16043 \pm 0.0338	0.30021 \pm 0.00175	2024 \pm 5	1846 \pm 6	1692 \pm 9	9%
23	85.65	226.99	1.10	0.19997 \pm 0.00216	13.35134 \pm 0.09631	0.4841 \pm 0.00307	2826 \pm 5	2705 \pm 7	2545 \pm 13	6%
27	161.44	273.23	0.66	0.13613 \pm 0.00143	6.3981 \pm 0.04283	0.34078 \pm 0.00202	2179 \pm 5	2032 \pm 6	1890 \pm 10	7%
32	138.83	290.96	0.28	0.13739 \pm 0.00162	7.82384 \pm 0.06811	0.41291 \pm 0.00275	2195 \pm 7	2211 \pm 8	2228 \pm 13	-1%
33	236.33	318.62	0.44	0.1131 \pm 0.00123	4.45062 \pm 0.03182	0.28534 \pm 0.0017	1850 \pm 6	1722 \pm 6	1618 \pm 9	6%
35	106.10	155.63	0.71	0.11922 \pm 0.00131	4.87636 \pm 0.03579	0.29659 \pm 0.00179	1945 \pm 6	1798 \pm 6	1674 \pm 9	7%
39	993.82	1181.67	0.14	0.11126 \pm 0.00113	3.95758 \pm 0.02362	0.25793 \pm 0.00147	1820 \pm 5	1626 \pm 5	1479 \pm 8	9%
40	785.76	950.21	0.08	0.11296 \pm 0.00093	4.08288 \pm 0.02479	0.26214 \pm 0.00147	1848 \pm 15	1651 \pm 5	1501 \pm 7	10%
42	58.29	92.45	0.92	0.11569 \pm 0.00141	4.9416 \pm 0.04488	0.30973 \pm 0.00202	1891 \pm 8	1809 \pm 8	1739 \pm 10	4%
50	188.73	264.41	0.44	0.11594 \pm 0.00128	4.66476 \pm 0.03486	0.29177 \pm 0.00177	1895 \pm 6	1761 \pm 6	1650 \pm 9	7%
54	110.55	204.77	0.78	0.14413 \pm 0.00153	7.42575 \pm 0.05059	0.37364 \pm 0.00224	2277 \pm 5	2164 \pm 6	2047 \pm 11	6%
55	267.60	350.80	0.42	0.11609 \pm 0.00127	4.38584 \pm 0.03202	0.27397 \pm 0.00165	1897 \pm 6	1710 \pm 6	1561 \pm 8	9%
56	145.36	240.43	0.35	0.12709 \pm 0.00135	6.0537 \pm 0.0412	0.34545 \pm 0.00206	2058 \pm 5	1984 \pm 6	1913 \pm 10	4%
65	80.40	183.31	0.96	0.17359 \pm 0.0023	10.0653 \pm 0.11343	0.42054 \pm 0.00294	2593 \pm 23	2441 \pm 10	2263 \pm 13	8%
68	282.81	321.82	0.43	0.11624 \pm 0.00128	4.59807 \pm 0.03397	0.28689 \pm 0.00174	1899 \pm 6	1749 \pm 6	1626 \pm 9	7%
70	295.90	367.06	0.51	0.1135 \pm 0.00125	4.03685 \pm 0.02961	0.25795 \pm 0.00155	1856 \pm 6	1642 \pm 6	1479 \pm 8	10%
71	77.22	191.29	0.78	0.16598 \pm 0.0018	10.88633 \pm 0.07948	0.47568 \pm 0.00299	2518 \pm 5	2513 \pm 7	2508 \pm 13	0%
72	156.56	346.99	1.13	0.16169 \pm 0.00169	9.21635 \pm 0.06111	0.4134 \pm 0.00248	2473 \pm 5	2360 \pm 6	2230 \pm 11	6%
75	137.54	229.92	1.00	0.13562 \pm 0.00155	6.15778 \pm 0.04942	0.3293 \pm 0.00209	2172 \pm 6	1998 \pm 7	1835 \pm 10	9%
77	85.47	115.13	0.79	0.11691 \pm 0.00149	4.45387 \pm 0.04366	0.27632 \pm 0.00186	1910 \pm 9	1722 \pm 8	1573 \pm 9	9%

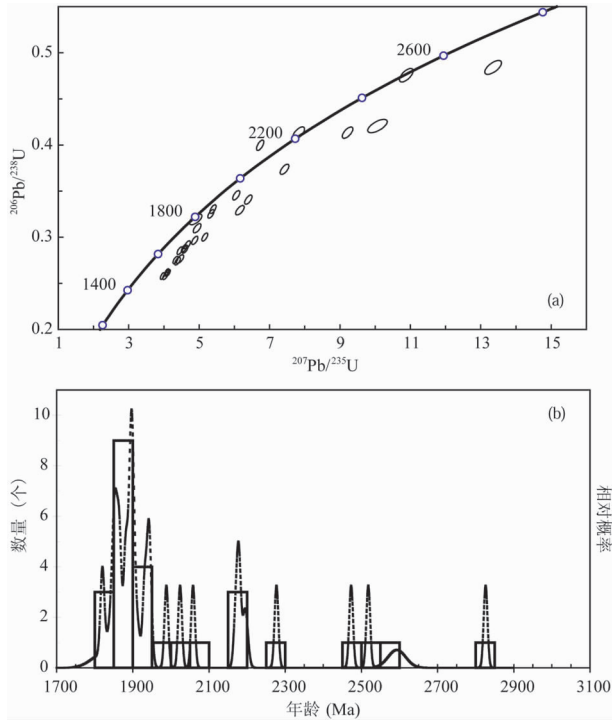


图3 下寒武统样品 03TB01 碎屑锆石谐和曲线(a)与 U-Pb 年龄谱图(b)

在(b)中直方图表示数量,虚曲线表示相对概率

Fig. 3 Concordia plots (a), number histograms (b, in real line) and probability plots (b, in dashed line) for detrital zircon ages of the Lower Cambrian sandstone samples (No. 03TB01)

概率峰值(图 3b)。该区间年龄数据的不谐和度为 0% ~ 8%,平均约 5%。该 3 颗碎屑锆石的 Th/U 比值均大于 0.4 (介于 0.78 ~ 1.13)(表 1);结合 CL 图分析(图 4),认为这组碎屑锆石大多显示出明显的内部分带结构,应属岩浆成因。

此外,样品 03TB01 最老的 1 个碎屑锆石 U-Pb 年龄为 2826Ma(图 3b),其不谐和度为 6%。该碎屑锆石的 Th/U 比值为 1.1(表 1),但根据 CL 图分析可能具有变质成因属性。

5.2 中-上石炭统(下二叠统?)样品 03TB09

在样品 03TB09 的 47 个 U-Pb 有效年龄中(表 2),34 个不谐和度小于 5%(占 72.3%),13 个不谐和度在 5% ~ 10% 之间(占 17.3%),其谐和曲线见图 5a。从年龄谱图上看(图 5b),U-Pb 有效年龄主要集中分布在 288 ~ 340Ma、461 ~ 474Ma、1780 ~ 1892、1941 ~ 1959、2012 ~ 2050Ma 等几个区间,并存在 3408Ma 的最老年龄数据。

288 ~ 340Ma 区间共有 10 个碎屑锆石 U-Pb 年龄,占该样品总有效数据的 21.3%,其算术平均值约为 311Ma,而相对概率峰值为 305Ma(图 5b)。该区间年龄数据的不谐和度为 -1% ~ 8%,平均值约 4%,是主要的和可信的年龄分布区间之一。在这组年龄中,Th/U 比值介于 0.73 ~ 1.71(表 1),显示以岩浆成因为主;但结合 CL 图揭示的颗粒结构分析(图 6),认为这组碎屑锆石中仍有约 19% 受到明显的变质(交代或重结晶)作用影响。

落入 461 ~ 474Ma 区间的有 2 个碎屑锆石,占总有效数据的 3.1%,其算术平均值约为 468Ma,而相对概率峰值为 474Ma(图 5b)。2 个年龄数据的不谐和度分别为 -2.0% 和

表 2 中-上石炭统(下二叠统?) Manhang 组砂岩样品(03TB09)碎屑锆石 U-Pb 年龄测定结果

Table 2 U-Pb dating data of sandstone detrital zircons (sample no. 03TB09) from the Manhang Formation, Middle-Upper Carboniferous (Lower Permian?)

点号	U ($\times 10^{-6}$)	Pb ($\times 10^{-6}$)	Th/U	同位素比值			表面年龄 (Ma)			不谐 和度
				$^{207}\text{Pb}/^{206}\text{Pb}(\pm 1\sigma)$	$^{207}\text{Pb}/^{235}\text{U}(\pm 1\sigma)$	$^{206}\text{Pb}/^{238}\text{U}(\pm 1\sigma)$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	
06	442.51	596.75	0.22	0.11111 ± 0.00115	4.28693 ± 0.02679	0.27979 ± 0.00158	1818 ± 5	1691 ± 5	1590 ± 8	6%
07	958.35	229.37	0.93	0.05532 ± 0.00124	0.34855 ± 0.00751	0.0457 ± 0.00029	425 ± 51	304 ± 6	288 ± 2	5%
08	488.40	777.36	0.27	0.11448 ± 0.00117	5.13021 ± 0.03115	0.32496 ± 0.00182	1872 ± 5	1841 ± 5	1814 ± 9	1%
09	443.64	657.41	0.14	0.11269 ± 0.00099	4.75248 ± 0.03199	0.30587 ± 0.00172	1843 ± 16	1777 ± 6	1720 ± 8	3%
10	326.94	526.25	0.10	0.11418 ± 0.00119	5.2344 ± 0.03302	0.33243 ± 0.00188	1867 ± 5	1858 ± 5	1850 ± 9	0%
11	195.90	315.23	0.44	0.11368 ± 0.00124	4.99828 ± 0.0354	0.31884 ± 0.00186	1859 ± 6	1819 ± 6	1784 ± 9	2%
12	183.04	304.78	0.34	0.11468 ± 0.00119	5.2484 ± 0.03294	0.33188 ± 0.00187	1875 ± 5	1861 ± 5	1847 ± 9	1%
16	367.11	90.08	0.73	0.05734 ± 0.00078	0.38136 ± 0.00403	0.04823 ± 0.00028	505 ± 13	328 ± 3	304 ± 2	8%
18	110.96	164.36	0.89	0.11381 ± 0.00131	4.38735 ± 0.03519	0.27956 ± 0.00168	1861 ± 7	1710 ± 7	1589 ± 8	7%
19	234.59	391.08	0.54	0.11242 ± 0.00125	4.98298 ± 0.03704	0.32145 ± 0.00189	1839 ± 6	1816 ± 6	1797 ± 9	1%
22	146.72	242.11	0.58	0.11543 ± 0.00131	4.85667 ± 0.03771	0.30512 ± 0.00181	1887 ± 7	1795 ± 7	1717 ± 9	4%
23	194.18	51.69	1.00	0.05441 ± 0.00091	0.3748 ± 0.00532	0.04995 ± 0.00031	388 ± 21	323 ± 4	314 ± 2	3%
24	94.62	162.61	0.69	0.11178 ± 0.00129	4.93058 ± 0.03934	0.31986 ± 0.00191	1829 ± 7	1808 ± 7	1789 ± 9	1%
25	223.16	365.04	0.23	0.11341 ± 0.00117	5.11921 ± 0.0311	0.32733 ± 0.00179	1855 ± 5	1839 ± 5	1825 ± 9	1%
26	166.92	67.36	0.73	0.06342 ± 0.00089	0.667 ± 0.00743	0.07627 ± 0.00045	722 ± 14	519 ± 5	474 ± 3	9%
30	200.74	356.10	0.48	0.11249 ± 0.00119	5.12273 ± 0.03309	0.33024 ± 0.00182	1840 ± 5	1840 ± 5	1840 ± 9	0%
32	314.91	434.91	0.37	0.10959 ± 0.00111	4.20549 ± 0.02525	0.2782 ± 0.00153	1793 ± 5	1675 ± 5	1582 ± 8	6%
33	494.99	749.96	0.40	0.11112 ± 0.00111	4.51929 ± 0.02549	0.29484 ± 0.00159	1818 ± 5	1735 ± 5	1666 ± 8	4%
35	484.11	131.76	0.78	0.05273 ± 0.00082	0.39331 ± 0.0051	0.05408 ± 0.00033	317 ± 18	337 ± 4	340 ± 2	-1%
36	1442.33	2145.91	0.18	0.10951 ± 0.00109	4.4951 ± 0.02456	0.29764 ± 0.00156	1791 ± 4	1730 ± 5	1680 ± 8	3%
37	347.08	559.03	0.31	0.1126 ± 0.00119	4.97358 ± 0.03199	0.32028 ± 0.00176	1842 ± 5	1815 ± 5	1791 ± 9	1%
39	132.29	224.50	0.36	0.11285 ± 0.00126	5.17881 ± 0.03855	0.33276 ± 0.00192	1846 ± 6	1849 ± 6	1852 ± 9	0%
42	433.91	805.51	0.45	0.12454 ± 0.00129	6.17551 ± 0.03796	0.35957 ± 0.00196	2022 ± 5	2001 ± 5	1980 ± 9	1%
44	259.84	437.86	0.62	0.11298 ± 0.00122	5.10369 ± 0.03455	0.32758 ± 0.00183	1848 ± 6	1837 ± 6	1827 ± 9	1%
45	148.30	247.65	0.46	0.11371 ± 0.00127	5.21463 ± 0.03871	0.33255 ± 0.00192	1860 ± 6	1855 ± 6	1851 ± 9	0%
48	417.66	102.44	0.80	0.05765 ± 0.00099	0.38556 ± 0.00568	0.0485 ± 0.0003	516 ± 21	331 ± 4	305 ± 2	8%
49	325.25	472.27	0.42	0.11417 ± 0.00127	4.60555 ± 0.03344	0.29255 ± 0.00167	1867 ± 6	1750 ± 6	1654 ± 8	6%
51	119.79	31.05	0.73	0.05232 ± 0.00124	0.37171 ± 0.00811	0.05152 ± 0.00038	299 ± 36	321 ± 6	324 ± 2	-1%
53	319.30	77.14	0.80	0.05541 ± 0.00088	0.37043 ± 0.00487	0.04848 ± 0.00029	429 ± 19	320 ± 4	305 ± 2	5%
55	172.19	54.75	0.97	0.05776 ± 0.00106	0.49288 ± 0.00786	0.06189 ± 0.0004	521 ± 24	407 ± 5	387 ± 2	5%
56	331.49	85.59	1.71	0.05559 ± 0.00107	0.35719 ± 0.00602	0.0466 ± 0.00031	436 ± 26	310 ± 5	294 ± 2	5%
57	119.62	32.33	1.50	0.05633 ± 0.00138	0.38918 ± 0.00879	0.0501 ± 0.00038	465 ± 36	334 ± 6	315 ± 2	6%
59	461.54	642.18	0.24	0.11286 ± 0.00101	4.42547 ± 0.03164	0.2844 ± 0.00155	1846 ± 17	1717 ± 6	1613 ± 8	6%
60	515.37	678.12	0.22	0.11419 ± 0.00121	4.30937 ± 0.02729	0.27367 ± 0.00149	1867 ± 5	1695 ± 5	1559 ± 8	8%
62	586.44	2172.72	0.52	0.28815 ± 0.00291	25.5789 ± 0.14193	0.64373 ± 0.00348	3408 ± 4	3331 ± 5	3204 ± 14	4%
63	765.87	208.64	1.66	0.05477 ± 0.00071	0.3821 ± 0.00364	0.05059 ± 0.00028	403 ± 12	329 ± 3	318 ± 2	3%
65	285.64	388.44	0.38	0.1158 ± 0.00129	4.55572 ± 0.03293	0.28529 ± 0.00163	1892 ± 6	1741 ± 6	1618 ± 8	7%
67	191.66	338.41	0.68	0.119 ± 0.00129	5.76232 ± 0.0389	0.35112 ± 0.00197	1941 ± 5	1941 ± 6	1940 ± 9	0%
68	281.31	544.20	0.32	0.12379 ± 0.00129	6.38763 ± 0.04355	0.3741 ± 0.00213	2012 ± 5	2031 ± 6	2049 ± 10	-1%
70	43.61	15.41	0.18	0.05454 ± 0.00202	0.55722 ± 0.01981	0.07408 ± 0.00073	393 ± 62	450 ± 13	461 ± 4	-2%
71	405.69	649.75	0.99	0.12021 ± 0.00129	4.80453 ± 0.03404	0.28986 ± 0.00165	1959 ± 6	1786 ± 6	1641 ± 8	8%
72	132.77	209.19	0.36	0.11278 ± 0.00143	4.72672 ± 0.04619	0.30395 ± 0.00198	1845 ± 9	1772 ± 8	1711 ± 10	4%
73	165.21	47.11	0.48	0.05493 ± 0.00121	0.43253 ± 0.00871	0.05711 ± 0.0004	409 ± 32	365 ± 6	358 ± 2	2%
74	132.35	212.25	0.18	0.10886 ± 0.0013	4.72732 ± 0.04168	0.31497 ± 0.00194	1780 ± 8	1772 ± 7	1765 ± 10	0%
79	156.19	253.11	0.57	0.11328 ± 0.00131	4.78474 ± 0.03872	0.30633 ± 0.00182	1853 ± 7	1782 ± 7	1723 ± 9	3%
80	127.95	246.88	0.43	0.12649 ± 0.00143	6.25156 ± 0.04814	0.35842 ± 0.00213	2050 ± 6	2012 ± 7	1975 ± 10	2%
84	485.66	734.75	0.33	0.11549 ± 0.00123	4.59383 ± 0.02969	0.28833 ± 0.00158	1888 ± 5	1748 ± 5	1633 ± 8	7%

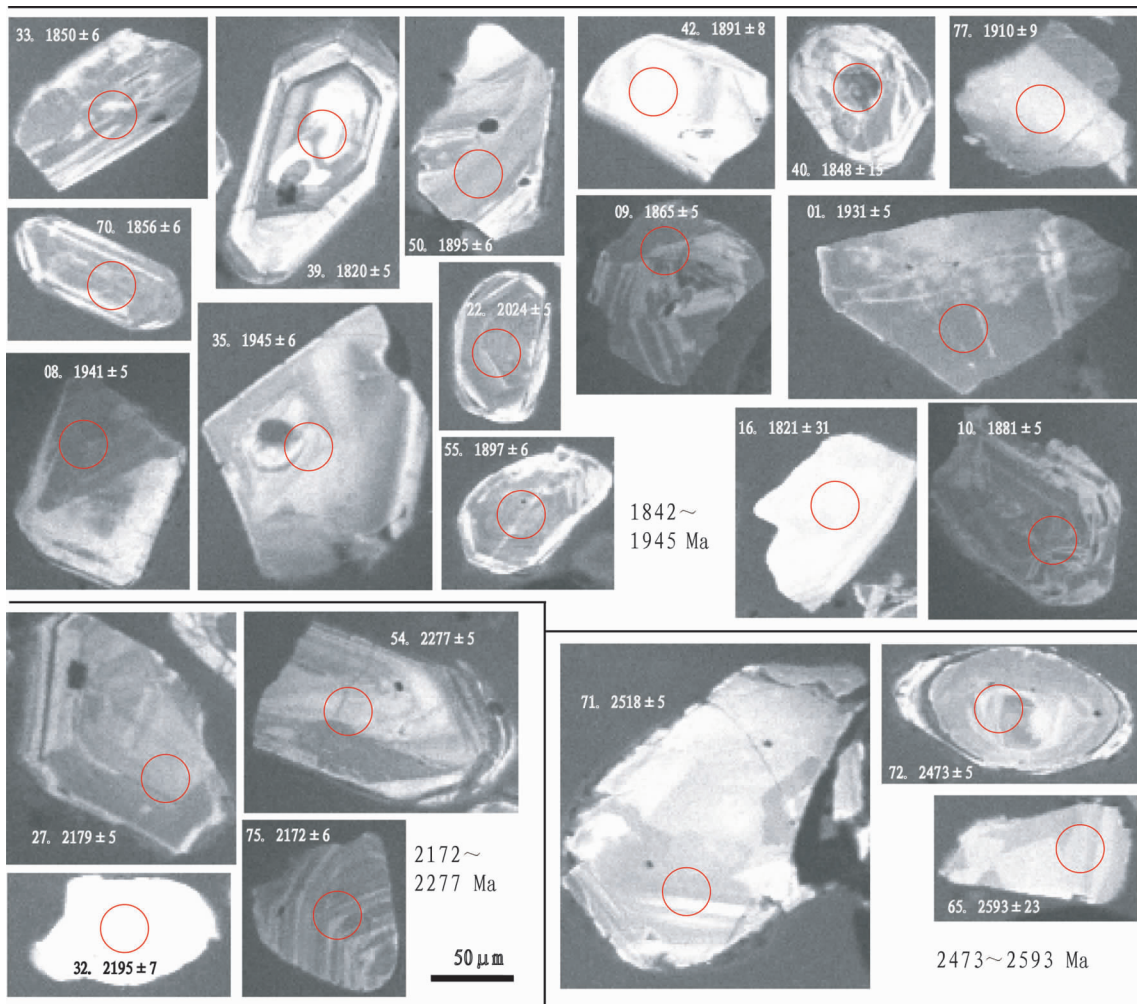


图4 下寒武统样品 03TB01 典型碎屑锆石 CL 图象

每张图象标示了原位测试点(圆圈)、测试点号(同表1)和 U-Pb 表面年龄

Fig. 4 Typical CL images for detrital zircons of the Lower Cambrian sandstone samples (No. 03TB01)

In-situ measure spots (circles), numbers (referred to Table 1) and U-Pb apparent ages are marked in each images

9.0%,虽不是主要的但却是基本可信的年龄分布区间;此外,其 Th/U 比值分别为 0.18 和 0.73(表1),结合 CL 图分析认为 Th/U 比为 0.18 的锆石可能具有变质成因(图6)。

1780 ~ 1892Ma 区间共有 27 个碎屑锆石 U-Pb 年龄,占该样品总有效数据的 57.4%,其算术平均值约为 1855Ma,而相对概率峰值为 1867Ma(图 5b)。该区间年龄数据的不谐和度为 0% ~ 8%,平均值约 3%,因此是最主要的和可信的年龄分布区间之一。在这组年龄中, Th/U 比值介于 0.1 ~ 0.89(表1)显示岩浆、变质(交代或重结晶)成因各存在约 50%。

1941 ~ 1959Ma 区间的 2 个碎屑锆石 U-Pb 年龄,占该样品总有效数据的 4.3%,其相对概率峰值为 1943Ma(图 5b),不谐和度分别为 0%、8%, Th/U 比值为 0.68、0.99(表1)显示岩浆成因特征。

2012 ~ 2050Ma 区间共有 3 个碎屑锆石 U-Pb 年龄,占该

样品总有效数据的 6.4%,其算术平均值约为 2028Ma,而相对概率峰值为 2019Ma(图 5b)。该区间年龄数据的不谐和度为 -1% ~ 2%,平均值约 1%。在这组年龄中, Th/U 比值介于 0.32 ~ 0.45(表1),显示变质(交代或重结晶)成因。

6 讨论

6.1 构造热事件及其年代限定

从研究区及周缘主要块体分析,已认识到的寒武纪、前寒武纪构造及岩浆、变质作用事件有:京畿和岭南地块分别发育 1862 ~ 1899 Ma 和 1835 ~ 1906 Ma 两组类似的变质及岩浆活动年龄(Sagong *et al.*, 2003),岭南地块西南缘记录了有争议的 1417 Ma 的变质年龄(Oh *et al.*, 2000; Sagong *et al.*, 2003),京畿地块南缘和岭南地块北缘存在 1198 ~ 956Ma 的岩浆、变质年龄(Lee *et al.*, 1994; Kim *et al.*, 2005; Sagong

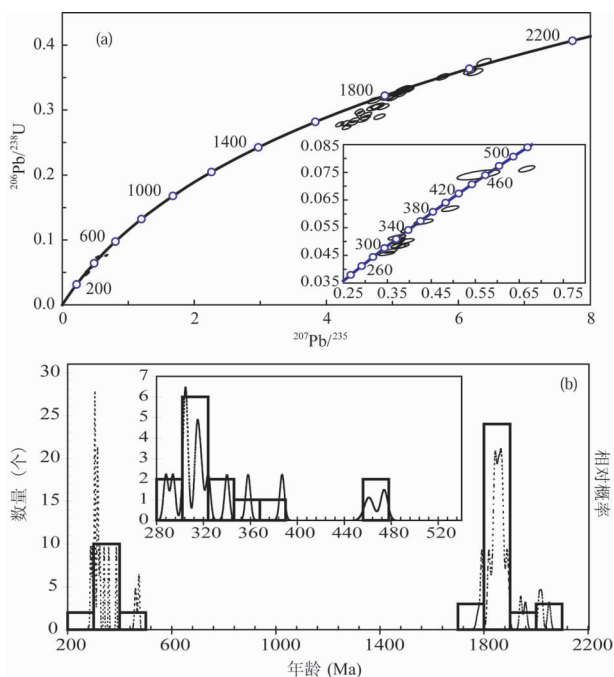


图5 中-上石炭统(下二叠统?)样品 03TB09 碎屑锆石谐和曲线(a)与 U-Pb 年龄谱图(b)

在(b)中直方图表示数量,虚曲线表示相对概率

Fig. 5 Concordia plots (a), number histograms (b, in real line) and probability plots (b, in dashed line) for detrital zircon ages of the Middle-Upper Carboniferous (Lower Permian?) sandstone samples (No. 03TB09)

et al., 2003), 京畿地块发育 850 ~ 742Ma 的岩浆侵入年龄(见 Oh, 2006 评述)等。而从寒武纪到石炭纪,主要有发育于京畿地块西部反映 335 ~ 473Ma 构造或岩浆、变质热事件的年龄(见 Oh, 2006 评述)。

太白山盆地下寒武统样品 03TB01 碎屑锆石 U-Pb 有效年龄记录了至少 4 期构造热事件,其中相对概率峰值为 1897Ma、2177Ma 以及平均值为 2528Ma 的 3 期构造热事件可信度相对较高。很明显,峰值为 1897Ma (1820 ~ 1945Ma 区间)的碎屑锆石不仅在样品 03TB01 中具有显著优势,而且与上述京畿和岭南地块发育的古元古代构造热事件年龄相当。碎屑锆石记录的另两组峰值为 2177Ma 和 2528Ma 的年龄,在相邻区域却未发现对应变质及岩浆热事件。另一方面,京畿地块(南缘)和岭南地块北缘发育的古一中元古代年龄却未在盆地寒武统碎屑锆石中找到记录。

中-上石炭统(下二叠统?)样品 03TB09 碎屑锆石 U-Pb 有效年龄主要记录了 5 期构造热事件,其中相对概率峰值为 305Ma、1867Ma 的两组年龄比较集中。峰值为 1867Ma 的年龄在区域上可与京畿和岭南的基底变质热事件对应,峰值为 305Ma (288 ~ 340Ma 区间)和 468Ma (461 ~ 474Ma 区间)的年龄则与发育于京畿地块西部反映 335 ~ 473Ma 构造或岩浆—变质事件基本可以对比。同理对比分析,京畿地块(南缘)和

岭南地块北缘发育的古-中元古代年龄也未在盆地样品 03TB09 的碎屑锆石中找到记录。

应该指出,样品 03TB09 最年轻一组碎屑锆石中,其年龄相对概率峰值为 305Ma,有 2 个有效数据小于 299Ma (不谐和度均为 5%),因此保守推断样品 03TB09 所在层位应更改为下二叠统,而因为样品 03TB09 取于紧靠奥陶系不整合面上的一层砂岩,所以研究剖面可能不发育石炭系。当然,这一推论尚需进一步查证,为此本文对样品 03TB09 所在层位的标定仍然沿用中-上石炭统(下二叠统?)(图 2),但标记问号。此外该组 U-Pb 年龄的构造意义也有待厘定。

6.2 源区与构造单元对比

在太白山盆地下寒武统和中-上石炭统(下二叠统?)两个样品记录的前寒武纪构造热事件中,显然最集中和可信的年龄均与相邻的京畿和岭南地块发育的古元古代基底变质年龄(1835 ~ 1906 Ma)相当,并与已经揭示的华北克拉通该时期的构造热事件(Lu *et al.*, 2003; Zhai and Liu *et al.*, 2003)类似,此外两个样品也存在可与华北克拉通对比的大约 2500Ma 的构造热事件记录(尽管京畿和岭南地块尚未发现);另一方面,两个样品也都缺乏华南地块普遍发育的新元古代岩浆活动年龄(Li *et al.*, 2003)。对此本文有如下两个推论:其一,研究样品的碎屑物源来自太白山盆地周缘较大流域范围特别是东部地区(Kwon *et al.*, 2006; Lee and Chough, 2006),因此太白山盆地至少与岭南地块存在密切的物源和构造亲属关系,而且其构造热事件的主峰年龄可与华北克拉通对比;其二,尽管朝鲜半岛中南部沃川带、京畿地块西缘和岭南地块北缘发现了可与华南新元古代岩浆活动类比的年龄(Lee *et al.*, 1998, 2003),但盆地中两个样品的碎屑锆石均缺乏这组年龄,说明至少在寒武纪至石炭纪期间,太白山盆地周缘并不存在与华南新元古代构造单元可以类比的块体,并由其向太白山盆地提供了碎屑物源;换言之,如果 Lee *et al.* (1998, 2003)的发现确实与华南块体有关,那它也并不代表这一地区的岩石圈整体属性,而很可能是石炭纪以后的外来块体拼贴、挤入或表层推覆的表现。这是否可以用 Li (1994)的地壳拆离(crustal-detachment)模式来解释尚需研究。

事实上,中-上石炭统(下二叠统?)样品记录的峰值为 305Ma 和 468Ma 的年龄极可能与发生在华北—朝鲜联合块体南缘的俯冲事件(Metcalf, 1996; Oh, 2006)有关,后者形成和强烈改造的岩石类型显然在晚石炭—二叠纪时已经影响到太白山盆地的沉积物源。而这一时期(晚古生代)亲华南的陆块(具有显著的新元古代构造记录)至少在晚石炭世(早二叠世?)以前并未向太白山盆地提供碎屑物源,也极可能还未与京畿—岭南等地块发生拼贴作用(如果有拼贴过程的话)。正因为如此,上石炭统(下二叠统?)的碎屑锆石样品仍然没有记录到新元古代的构造热事件。

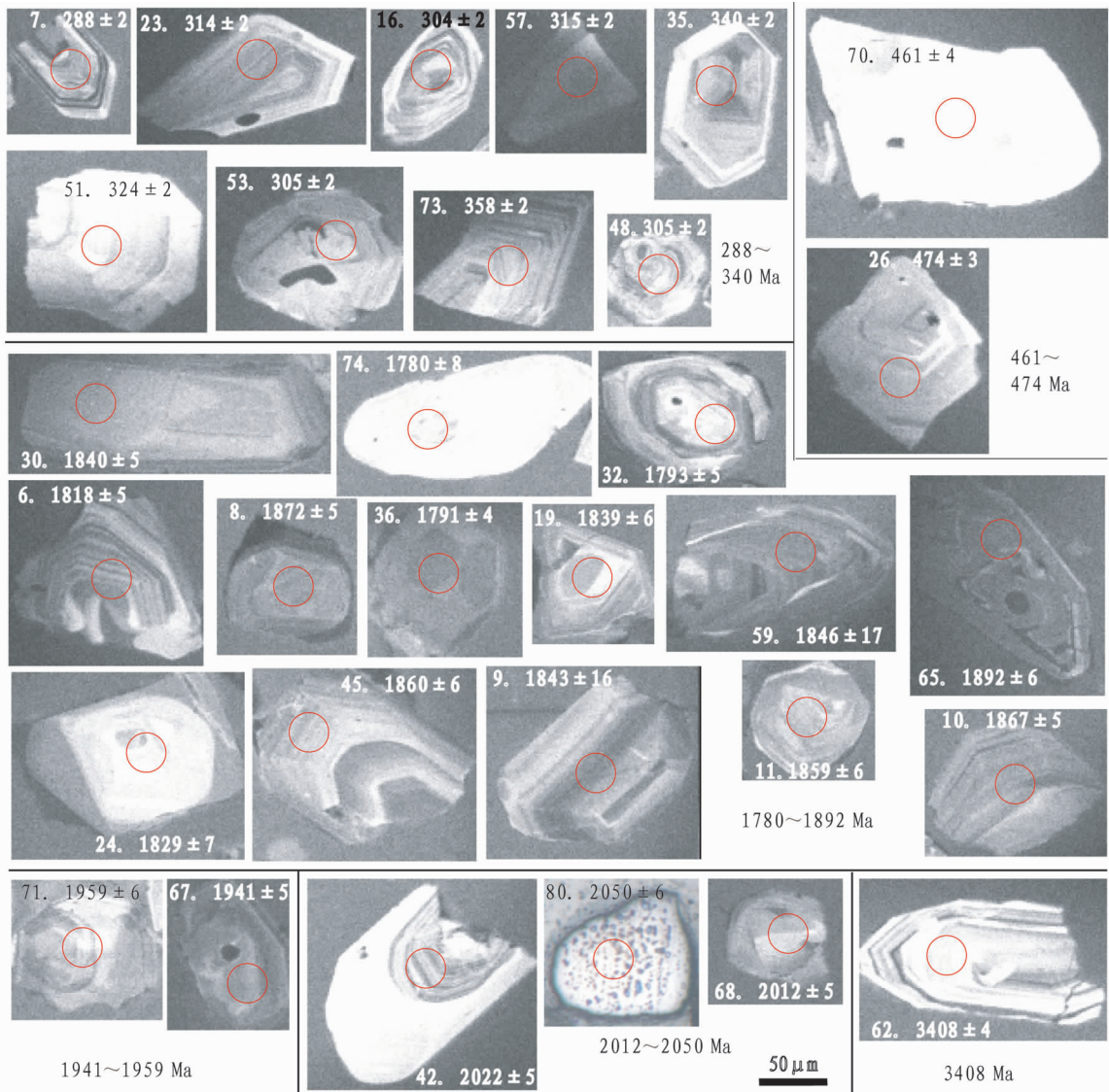


图6 中-上石炭统(下二叠统?)样品 03TB09 典型碎屑锆石 CL 图象

每张图象标示了原位测试点(圆圈)、测试点号(同表1)和 U-Pb 表面年龄

Fig. 6 Typical CL images for detrital zircons of the Middle-Upper Carboniferous (Lower Permian?) sandstone samples (No. 03TB09)

In-situ measure spots (circles), numbers (referred to Table 2) and U-Pb apparent ages are marked in each images

7 结论

(1) 通过 LA-ICP-MS 方法,从太白山盆地下寒武统、中-上石炭统(下二叠统?)碎屑锆石中分别获得 27 个和 47 个 U-Pb 有效年龄,前者记录了 1820 ~ 1945Ma、2172 ~ 2195Ma、2473 ~ 2593Ma 等构造热事件,其中相对概率峰值为 1897Ma、2177Ma 以及平均值为 2528Ma 的三期年龄可信度较高;后者主要记录了 288 ~ 340Ma、461 ~ 474Ma、1780 ~ 1892、1941 ~ 1959、2012 ~ 2050Ma 等构造热事件,其中相对概率峰值为 305Ma 和 1867Ma 的两组年龄比较集中。

(2) 太白山盆地与京畿、岭南两个地块均发育大约 1850Ma 的构造热事件,缺乏新元古代构造热事件;由于太白山盆地下寒武统、中-上石炭统(下二叠统?)碎屑物源主要来自盆地东部较大流域范围,这至少说明太白山盆地与岭南地块之间存在密切的物源和构造关系,并可与华北克拉通对比。

(3) 中-上石炭统(下二叠统?)样品记录了峰值为 305Ma 和 468Ma 可能发生在华北一朝鲜联合壳体南缘的构造热事件;另一方面,下寒武统、中-上石炭统(下二叠统?)两个样品的碎屑锆石均缺乏华南比较特征的新元古代构造热事件的年龄记录,说明亲华南的陆块至少在晚石炭世(早二

叠世?) 以前并未向太白山盆地提供碎屑物源。

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