

准噶尔盆地西北缘克百断裂带晚石炭世火山岩成吉思汗山组新认识及其地质意义

——来自百乌21井LA-ICP-MS锆石U-Pb定年与地震资料的证据

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摘要:克百断裂带是准噶尔盆地西北缘晚古生代构造-地层演化与油气勘探的关键区带,区内石炭世火山岩地层归属长期存在争议。以克百断裂带百乌21井钻遇的原被视为早二叠世佳木河组的火山岩系为研究对象,通过综合岩石组合分析、LA-ICP-MS锆石铀(U)-铅(Pb)定年和地震剖面解释,重新厘定了该套火山岩的层位归属。研究结果表明:①百乌21井火山岩系两件凝灰质砂砾岩样品获得的火山岩碎屑锆石U-Pb年龄分别为 $311.9\text{ Ma} \pm 2.2\text{ Ma}$ 和 $311.6\text{ Ma} \pm 2.2\text{ Ma}$,限定其形成时代为晚石炭世晚期,归为成吉思汗山组(C_2c);②该套岩石组合特征以杏仁状安山岩和玄武安山岩为主,具有亚碱性、富钠贫钾的地球化学特征,与区域上 C_2c 的特征一致,而与佳木河组(P_1jm)存在显著差异;③地震剖面解析证实,该套地层与下伏地层下石炭统包古图组(C_1b)呈角度不整合接触,与区域上 C_2c 的底界构造特征一致,与 P_1jm 的层序叠置关系不同。综合上述证据,将该套火山岩重新厘定为成吉思汗山组。该新认识解决了该区长期存在的地层划分争议,完善了准噶尔盆地西北缘晚古生代地层格架,为古亚洲洋西段闭合时限与构造演化过程提供了新的年代学约束,同时也为准噶尔盆地西北缘石炭系深层油气勘探拓展了新的层系与方向。

关键词:LA-ICP-MS锆石U-Pb定年;地质年代学;地层厘定;成吉思汗山组;克百断裂带;准噶尔盆地西北缘

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New insights into Late Carboniferous volcanic rocks of the Chengjisihanshan Formation in the Kebai fault zone, northwestern margin of the Junggar Basin, and their geological significance: Evidence from LA-ICP-MS zircon U-Pb dating and seismic data in well Baiwu 21

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Abstract: The Kebai fault zone is a critical area for the Late Paleozoic tectono-stratigraphic evolution and hydrocarbon exploration along the northwestern margin of the Junggar Basin. The stratigraphic assignment of the Carboniferous volcanic rocks in the fault zone has long been a controversial issue. The volcanic rock sequence encountered in well Baiwu 21 within the Kebai fault zone, previously assigned to the Early Permian Jiamuhe Formation, was selected as the research object. Integrated lithological association analysis, LA-ICP-MS zircon U-Pb dating, and seismic profile interpretation were conducted on this sequence to redefine its stratigraphic assignment. As indicated by the research results, (1) the volcanoclastic zircon U-Pb ages obtained from two tuffaceous sandy conglomerate samples of the volcanic rock sequence in well Baiwu 21 are $(311.9 \pm 2.2)\text{ Ma}$ and $(311.6 \pm 2.2)\text{ Ma}$, respectively, indicating a formation age

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of the late stage of Late Carboniferous and reassigning the sequence to the Chengjisihanshan Formation (C_2c). (2) The rock suite is dominated by amygdaloidal andesite and basaltic andesite, exhibiting subalkaline, sodium-rich, and potassium-poor geochemical characteristics that are regionally consistent with those of the C_2c , but markedly distinct from those of the Jiamuhe Formation (P_1jm). (3) Seismic profile interpretation confirms that this stratigraphic unit has an angular unconformity contact with the underlying Lower Carboniferous Baogutu Formation (C_1b), mirroring the basal structural boundaries of the regional C_2c rather than the sequence stacking pattern of P_1jm . Consequently, these multiple lines of evidence justify the redefinition of this volcanic rock sequence as part of the Chengjisihanshan Formation. This new insight resolves the long-standing controversy over stratigraphic division in the area, refines the Late Paleozoic stratigraphic framework along the northwestern margin of the Junggar Basin, and provides fresh chronological constraints on the closure timing and tectonic evolution of the western Paleo-Asian Ocean. Furthermore, it opens up new strata and horizons for deep Carboniferous hydrocarbon exploration in the northwestern margin of the Junggar Basin.

Key words: LA-ICP-MS zircon U-Pb dating, geochronology, stratigraphic redefinition, Chengjisihanshan Formation, Kebai fault zone, northwestern margin of the Junggar Basin

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火山岩油气藏在近二十年得到了充分开发并已取得重大突破^[1-21]。准噶尔盆地西北缘是中国首批进行火山岩油气藏开发的区域^[22-26],近年来聚焦于老区开发,取得了丰富成果。准噶尔盆地西北缘位于中亚造山带西南段,是古亚洲洋俯冲-增生-闭合的核心记录区,其晚古生代地层格架与构造演化是解析中亚造山带大陆增生机制和古亚洲洋闭合的关键科学问题^[27-30]。克百断裂带作为盆地西北缘的重要构造单元,经历了海西期以来多期次的构造-岩浆活动,形成了多期次、多类型的火山-沉积地层序列^[31]。

长期以来,克百断裂带石炭系-二叠系火山岩地层的划分与对比存在争议,核心聚焦于佳木河组(P_1jm)和成吉思汗山组(C_2c)的时代限定、岩性标志和空间展布规律^[32-34]。传统观点将区内钻遇的火山岩系多划归上二叠统佳木河组,认为其是盆地西北缘二叠系重要的油气储集层;而成吉思汗山组则被限定为晚石炭世海相碎屑岩地层^[35]。近年来,高精度同位素定年技术的广泛应用为准噶尔盆地西北缘克百断裂带晚古生代火山岩系的地层划分与时代限定提供了重要依据。前人通过对原划归佳木河组的部分火山岩系开展锆石铀(U)-铅(Pb)定年研究后,将准噶尔盆地西北缘晚古生代岩浆活动分为两期:早石炭世(346.0~321.0 Ma)和晚石炭-早二叠世(316.0~281.0 Ma)^[36],这些年龄数据对传统地层划分方案提出了数据支持。

目前,佳木河组现已厘定为分布于准噶尔盆地西北缘乌尔禾以北哈拉阿拉特地区的一套冲积扇-扇三角洲相磨拉石建造,岩性组合以砾岩、含砾砂岩和中砂岩等陆相磨拉石为特征^[37]。尽管该区域尚未获得锆石测年数据,但其上覆的白杨河组(286.3 Ma)及下部不整合接触的阿腊德依克赛组均已取得可靠的测年数据或化石证据^[38-39],近年来,针对玛湖凹陷等盆地内佳木河组地层研究发现,其与西北缘山区露头地层存在较大差异^[40],并非简单的“下碎屑岩上火山岩”^[41]。由于本研究区地处克百断裂带,选择与西北缘山区露头地层进行对比更为合理。同时,不同学者对成吉思汗山组的定义、层型和区域对比方案也存在分歧。部分研究提出废弃原太勒古拉组、新建成吉思汗山组的方案,但在盆地覆盖区的识别与对比仍缺乏钻井-地震联合约束^[42-43]。

综上所述,当前克百断裂带晚古生代地层研究存在3个核心科学问题:①缺乏覆盖区钻井火山岩的高精度年代学数据,无法精准限定地层形成时代;②缺乏系统的岩相学-地球化学标志,难以有效区分成吉思汗山组与佳木河组火山岩;③缺乏井震结合的区域地层格架,无法实现露头区与覆盖区的地层对比。针对上述问题,本研究选取克百断裂带百乌21井为研究对象,通过岩心观察、地震剖面解释和U-Pb测年,系统厘定该井火山岩系的形成时代与地层归属,完善准噶尔盆地西北缘克百断裂带古生代地层格架,并探讨其构

造演化与油气勘探意义,为区域地质研究与深层油气勘探提供关键依据。

1 区域地质背景

克百断裂带位于准噶尔盆地西北缘,是一条大型逆掩推覆大断裂,其形成和演化受到准噶尔盆地西北缘褶皱带和准噶尔中间地块的控制(图1)。该断裂带

经历了中-晚海西期、印支期、燕山期及喜马拉雅运动等多期构造活动的叠加改造^[44],不仅控制着古生代地层的沉积与展布,也制约了油气的运移与聚集^[45-46]。

区域上,准噶尔盆地西北缘晚古生代地层发育完整,自下而上依次发育下石炭统太勒古拉组(C_{1t})、包古图组(C_{1b})、希贝库拉斯组(C_{1x}),上石炭统成吉思汗山组(C_{2c})、哈拉阿拉特组(C_{2h})、阿腊德依克赛组(C_{2al}),和下二叠统佳木河组(P_{1jm})、风城组(P_{1f})^[47]。

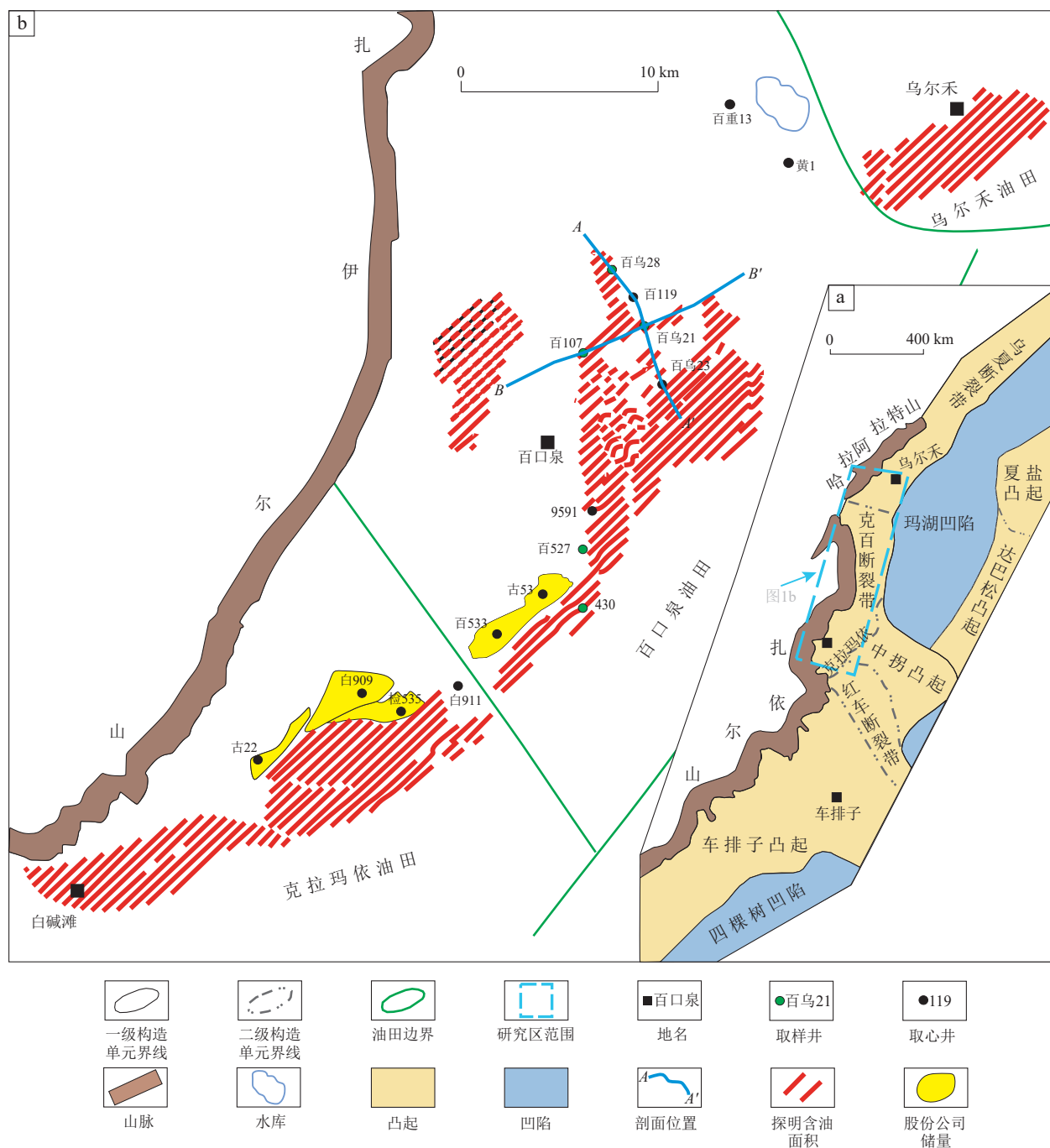


图1 准噶尔盆地西北缘克百断裂带构造位置(a)(修改自文献[60])和克拉玛依-百口泉地区简图(b)(修改自文献[61])

Fig. 1 Tectonic location of the Kebai fault zone along the northwestern margin of the Junggar Basin (a) (modified after reference [60]) and simplified map of the Karamay-Baikouquan area (b) (modified after reference [61])

其中, C_{1x} 以火山岩和海相沉积碎屑岩为主, C_{1b} 为火山岩与海相碎屑岩互层^[48-51]。

传统定义的 C_{1t} 由新疆地质局区测队 1966 年创名, 但其岩性组合复杂, 包含了不同时代、不同构造环境的地质体, 已不符合岩石地层单元中“组”的定义^[52]。近年来, 多数研究提出废弃该组名, 并以成吉思汗山组替代原太勒古拉组的上部层位^[40, 53]。成吉思汗山组层型位于克拉玛依市以北成吉思汗山一带, 其底界以一套底砾岩与下伏早石炭世地层呈角度不整合接触。其岩石组合可以划分为两部分: 下段以凝灰质砂砾岩类为主; 上段为凝灰岩、玄武岩、安山岩与硅质岩互层, 火山岩占比显著增高, 是晚石炭世区域岩浆活动直接记录。已发表的锆石 U-Pb 年龄集中在 312 Ma, 显示其形成时代为晚石炭世莫斯科期^[54]。 P_{1jm} 和 P_{1f} 与下伏石炭系地层呈角度不整合接触。传统认为, P_{1jm} 主要为火山岩系, 而 P_{1f} 则发育白云岩和白云质泥岩等沉积岩^[55-59]。受长期地质构造作用影响, 克百断裂带上、下盘地层发育差异显著: 上盘缺失二叠系和三叠系百口泉组, 仅局部残留三叠系的克拉玛依组和白碱滩组, 下盘地层发育完整, 石炭系—侏罗系均有分布, 沉积厚度大, 是油气勘探的主要目标区。

2 样品采集与分析测试方法

本次研究的样品均取自克百断裂带百乌 21 井岩心, 取样井段埋深为 1 523.25 ~ 1 530.10 m, 共采集岩心样品 15 件。取样层位原地质报告划归为下二叠统佳木河组, 岩性主要为凝灰质砂砾岩、岩屑凝灰岩和安山岩等。对采集的岩心样品进行系统宏观描述与编录, 制作标准岩石薄片, 通过透反射偏光显微镜进行岩相学观察、矿物成分鉴定和结构分析, 完成岩石类型定名与成岩蚀变特征研究。

锆石单矿物挑选在廊坊市宇弘岩矿科技有限公司完成。经破碎、重选和磁选后, 在双目镜下挑选出晶形完整、无裂隙的锆石颗粒。锆石制靶、抛光, 并进行透反射和阴极发光(CL)图像拍摄, 以上操作均在北京铅年领航科技有限公司完成。通过 CL 图像识别锆石的内部结构, 筛选岩浆成因锆石环带区域作为测年靶位。LA-ICP-MS 锆石 U-Pb 同位素测试在中国地质科学院地质力学所完成, 采用德国耶拿分析仪器公司的 PQ-MS 电感耦合等离子体质谱仪和 ESL 公司的 NWR193nm 高能 ArF 激光器联用系统。测试激光束斑和频率分别为 30 μm 和 5 Hz, 每个测点的分析流程包括 20 ~ 30 s 空白信号和 40 s 样品信号采集。测试过程中采用锆石

标准 91500 和玻璃标准物质 NIST610 分别进行同位素分馏和微量元素含量校正, 每测试 10 个样品点, 穿插测试 2 个标样点和 1 个监控样点, 保证测试精度。测试数据的离线处理(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及 U-Pb 同位素比值和年龄计算)采用软件 *iolite4* 完成, 锆石 U-Pb 年龄谐和图绘制和年龄加权平均计算采用 *Isoplot/Ex_ver3*^[62] 完成。

BW21-2 样品变质岩屑凝灰岩样品取样深度为 1 523.56 m(图 2), 岩石具变质火山凝灰结构, 变余假流纹构造。岩石主要由变余岩屑及基质组成, 副矿物见不透明金属矿物。岩石整体发育强硅化明显, 且整体发育强烈变质作用。岩屑主要为燧石和含泥质硅质岩, 呈次棱角状, 粒径介于 0.38 ~ 0.86 mm, 最大者约 1.40 mm。燧石及泥质硅质岩均受重结晶作用, 向微晶石英及雏晶云母过渡, 另见岩屑内吸附有少量铁质组份。

BW21-4 样品凝灰质砂砾岩样品取样深度为 1 529.60 m(图 2), 岩石具凝灰质砂砾结构, 块状构造。砾石主要由晶屑和凝灰岩组成, 胶结物主要为火山灰和砂粒, 副矿物见不透明金属矿物。岩石整体支撑类型为基质支撑, 胶结类型为基底式胶结。砾石成分包括: ①凝灰岩, 呈次棱角状, 粒径介于 1.78 ~ 3.75 mm, 具凝灰结构, 块状构造, 部分发育强烈褐铁矿化, 色较暗; ②单晶石英、钾长石构成的砾石, 呈次棱角状—次圆状, 粒径介于 2.00 ~ 2.59 mm。单晶石英呈次棱角状, 晶内裂纹发育, 具平行消光。钾长石呈次棱角状, 多为微斜长石, 格子双晶发育明显, 另见少量条纹长石, 条纹结构可见。

本次研究采用的三维地震资料由新疆油田公司百口泉采油厂提供, 覆盖克百断裂带全区, 地震资料主频介于 30 ~ 50 Hz, 垂向分辨率较高。首先, 通过百乌 21 井的声波测井与密度测井数据制作合成地震记录, 完成井震标定, 将钻井岩性—地层界面精准对应到地震剖面; 在此基础上, 搭建过百乌 21 井的两条连井地震剖面, 完成层位追踪、不整合面识别和构造解释, 建立区域地层格架。

3 研究结果

3.1 岩石组合特征

研究区岩性主要为火山熔岩(安山岩和玄武质安山岩), 均发生不同程度的蚀变; 其次为火山碎屑岩(晶屑凝灰岩)和火山碎屑沉积岩(凝灰质砂砾岩)。岩石

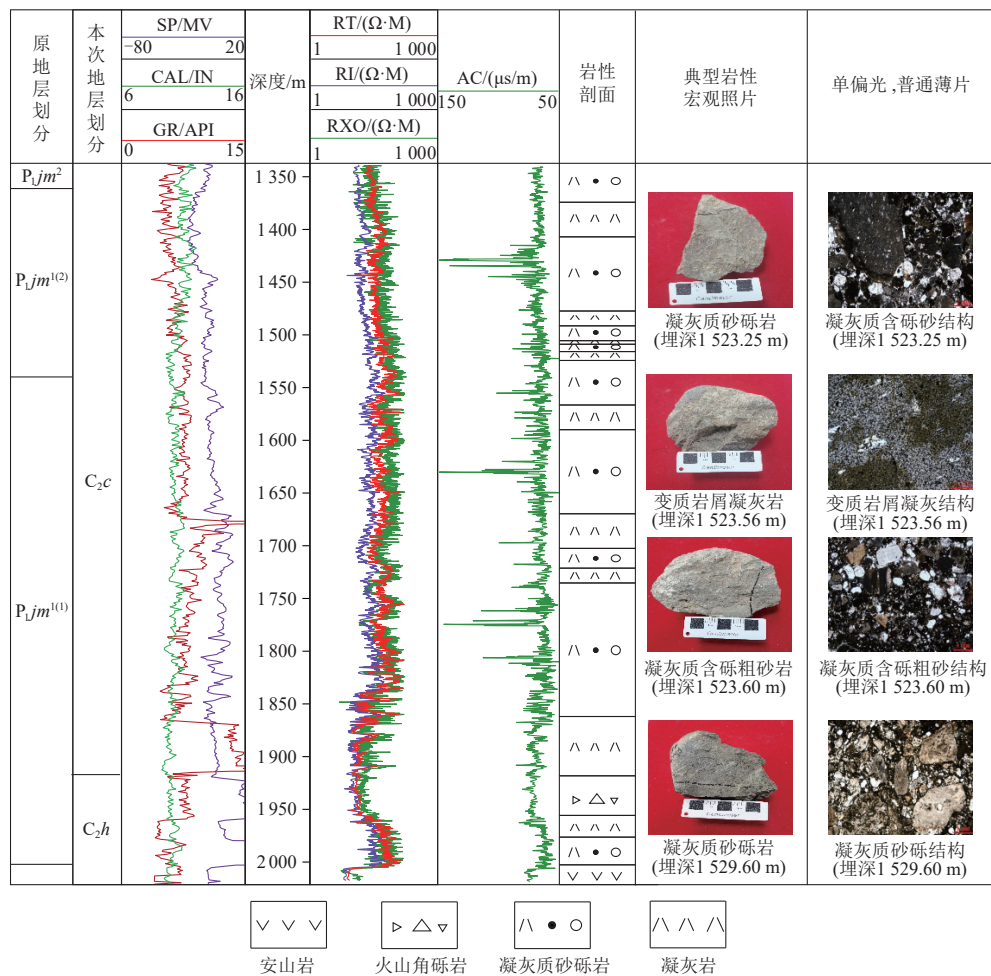


图2 准噶尔盆地西北缘克百断裂带百乌21井单井综合柱状图

Fig. 2 Comprehensive stratigraphic column of well Baiwu 21 in the Kebai fault zone, northwestern margin of the Junggar Basin
 $P_{1jm}^{1(1)}$. 下二叠统佳木河组一段一亚段; $P_{1jm}^{1(2)}$. 下二叠统佳木河组一段二亚段; P_{1jm}^2 . 下二叠统佳木河组二段; C_{2c} . 上石炭统成吉思汗山组

具凝灰质砂砾结构。胶结物主要为火山灰，副矿物见不透明金属矿物^[63]。岩石整体支撑类型为颗粒支撑，局部见基质支撑，胶结类型为孔隙式(图2)。该岩石组合与区域上成吉思汗山组上段的火山岩组合高度吻合，而与玛湖凹陷周缘佳木河组以中-酸性火山岩为主的岩性组合存在显著差异。

3.2 碎屑锆石 LA-ICP-MS 年代学结果

本次研究对 BW21-1 样品(埋深 1 523.25 m)和 BW21-15 样品(埋深 1 530.10 m)两个样品进行 LA-ICP-MS 锆石 U-Pb 定年。每件样品测试 30 个点，最终分别筛选出 22 个谐和度大于 90% 的有效测点(表 1)。

BW21-1 样品多呈自形-半自形棱柱状，粒径介于 50 ~ 180 μm，长/宽比介于 1.1 ~ 2.4。钍(Th)/铀(U)比值较高，介于 0.36 ~ 1.07(>0.1)。Th 含量为(11.77 ~ 271.61) × 10⁻⁶，U 含量为(32.80 ~ 349.73) × 10⁻⁶(表 1)。

铅-206 (²⁰⁶Pb)/铀-238 (²³⁸U) 年龄值介于 289.57 ~ 339.00 Ma，²⁰⁶Pb/²³⁸U 加权平均年龄为 311.9 Ma ± 2.2 Ma [平均标准权重偏差(MSWD) = 2.7](图 4a)，代表该套地层的最大沉积年龄。

BW21-15 样品的锆石多呈棱柱状，个别颗粒具磨圆度，粒径介于 50 ~ 160 μm，长/宽比介于 1.1 ~ 2.2。Th/U 比值较高，介于 0.36 ~ 1.07。Th 含量为(11.36 ~ 593.75) × 10⁻⁶，U 含量为(32.55 ~ 593.75) × 10⁻⁶(表 1)。²⁰⁶Pb/²³⁸U 年龄值介于 294.34 ~ 331.77 Ma，²⁰⁶Pb/²³⁸U 加权平均年龄为 311.60 ± 2.40 Ma (MSWD = 2.1)(图 4b)。

两件样品锆石普遍具有清晰震荡环带(图 3)，无明显变质增生边，指示其为岩浆成因^[64]。每块样品 22 个数据点集中分布在谐和曲线附近(图 4a,b)，代表该套地层碎屑物质沉积集中形成时间。两件样品的加权平均年龄为 311.6 ~ 311.9 Ma，属于上石炭统 C_{2c} ，远早于下二叠统 P_{1jm} 的形成时代，而与区域上成吉思汗

表 1 准噶尔盆地西北缘克百断裂带乌 21 井上石炭统凝灰质砂砾岩 LA-ICP-MS 锆石 U-Pb 同位素年龄
Table 1 LA-ICP-MS zircon U-Pb isotopic ages for the Upper Carboniferous tuffaceous sandy conglomerate from well Baiwu 21 in the Kebai fault zone, northwestern margin of the Junggar Basin

测点	元素含量/ 10^{-6}				$\frac{^{232}\text{Th}}{^{238}\text{U}}$		$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		同位素比值		$\frac{^{207}\text{Pb}}{^{238}\text{U}}$		年龄及误差		协和度
	Pb	Th	U		$\pm\%$	$\pm\%$	$\pm\%$	$\pm\%$	$\pm\%$	$\pm\%$	$\pm\%$	$\pm\%$	σ	σ	
BW21-1-1	6.17	44.05	73.43	0.60	0.05	0.01	0.35	0.05	403.29	32.35	311.26	12.35	304.62	41.99	97.87
BW21-1-2	17.67	123.79	216.50	0.57	0.05	0	0.37	0.03	173.46	345.59	305.25	7.41	314.98	19.75	96.81
BW21-1-3	3.56	19.71	44.67	0.44	0.05	0.01	0.39	0.07	453.79	225.69	315.58	13.89	320.89	54.39	98.32
BW21-1-4	2.78	20.09	48.80	0.41	0.06	0.02	0.38	0.11	786.31	-248.86	305.81	15.55	295.92	74.57	96.76
BW21-1-5	29.66	190.98	178.22	1.07	0.06	0.01	0.42	0.05	284.36	0	339.00	10.79	348.89	33.80	97.08
BW21-1-6	22.18	151.40	155.36	0.97	0.05	0.01	0.39	0.04	248.82	0	325.03	11.77	337.43	31.59	96.18
BW21-1-8	5.76	39.80	79.98	0.50	0.05	0.01	0.38	0.07	454.58	-128.18	335.38	12.55	317.46	48.55	94.66
BW21-1-9	2.86	18.12	40.93	0.44	0.06	0.01	0.37	0.09	605.26	-33.54	308.67	18.39	295.45	64.72	95.72
BW21-1-10	18.52	132.94	349.73	0.38	0.06	0	0.37	0.03	156.87	338.67	308.82	5.31	318.86	19.03	96.75
BW21-1-12	2.81	17.63	43.05	0.41	0.05	0.01	0.36	0.06	409.94	79.38	315.59	15.05	300.15	45.11	95.11
BW21-1-14	2.83	17.19	45.63	0.38	0.06	0.01	0.33	0.08	680.55	-224.65	307.10	15.17	286.71	62.87	93.36
BW21-1-15	3.11	25.68	51.08	0.50	0.05	0.01	0.36	0.09	617.85	-22.47	304.70	16.72	289.40	61.97	94.98
BW21-1-16	4.28	27.80	49.06	0.57	0.05	0.01	0.35	0.07	379.56	320.64	308.60	14.93	292.01	52.75	94.62
BW21-1-17	1.77	11.77	32.84	0.36	0.06	0.02	0.35	0.10	529.28	655.97	289.57	15.86	278.53	75.24	96.19
BW21-1-21	4.24	29.44	55.06	0.53	0.05	0.01	0.36	0.07	564.66	-244.09	310.87	13.94	298.01	49.76	95.86
BW21-1-22	30	212.03	231.81	0.91	0.05	0	0.33	0.03	257.95	14.56	307.90	8.65	292.78	26.11	95.09
BW21-1-23	39.67	271.61	276.86	0.98	0.05	0	0.37	0.03	165.50	346.66	308.92	8.38	315.98	20.89	97.71
BW21-1-24	5.15	34.36	32.80	1.05	0.05	0.01	0.37	0.10	438.20	269.49	316.74	18.63	296.79	71.67	93.70
BW21-1-26	3.05	21.57	53.86	0.40	0.06	0.01	0.41	0.07	400.20	494.16	312.28	15.53	335.00	46.99	92.73
BW21-1-27	5.25	33.20	66.11	0.50	0.05	0.01	0.35	0.06	309.78	311.99	295.46	13.72	294.49	42.54	99.67
BW21-1-29	4.79	27.70	60.16	0.46	0.06	0.01	0.43	0.08	455.24	327.52	324.18	15.67	347.77	54.01	92.72
BW21-1-30	13.42	92.14	197.33	0.47	0.06	0.01	0.38	0.04	277.16	390.90	303.02	9.51	325.33	32.68	92.64
BW21-1-5-1	4.48	29.62	67.09	0.44	0.06	0.01	0.38	0.08	477.71	117.11	324.9	14.25	315.69	53.48	97.17
BW21-1-5-2	3.66	24.27	50.39	0.48	0.06	0.01	0.39	0.08	614.14	47.48	316.69	11.42	329.76	63.58	95.87
BW21-1-5-3	3.05	21.51	44.12	0.49	0.05	0.01	0.34	0.07	625.52	-380.69	294.34	15.13	279.09	54.84	94.82
BW21-1-5-6	12.47	83.31	172.91	0.48	0.05	0.01	0.35	0.04	301.61	86.12	309.94	8.23	301.94	30.35	97.42
BW21-1-5-7	3.6	20.85	39.93	0.52	0.05	0.01	0.36	0.09	598.72	56.45	316.73	17.55	291.04	63.49	91.89
BW21-1-5-8	19.81	119.12	132.39	0.90	0.05	0	0.35	0.04	223.4	97.44	331.77	10.42	311.61	23.26	93.92
BW21-1-5-12	1.90	11.77	32.55	0.36	0.05	0.01	0.36	0.09	522.36	296.63	316.15	16.84	292.52	67.95	92.52
BW21-1-5-13	34.27	230.17	394.03	0.58	0.05	0	0.36	0.03	190.92	234.68	310.67	6.89	311.06	23.09	99.87
BW21-1-5-14	1.98	13.14	38.32	0.34	0.06	0.01	0.4	0.1	521.96	208.37	308.25	15.33	313.51	69.27	98.29
BW21-1-5-17	5.13	33.16	57.62	0.58	0.06	0.01	0.38	0.06	290.83	526.88	305.88	15.53	329.65	47.69	92.23
BW21-1-5-18	7.13	47.48	125.93	0.38	0.06	0.01	0.39	0.04	248.36	409.04	309.6	10.28	332.06	31.08	92.75
BW21-1-5-19	22.86	178.43	283.11	0.63	0.06	0.01	0.37	0.04	266.23	327.3	298.88	7.21	314.39	28.96	94.81
BW21-1-5-20	7.92	47.24	93.18	0.51	0.06	0.01	0.39	0.06	413.98	153.8	326.8	12.95	322.5	44.56	98.68
BW21-1-5-21	3.48	25.66	54.72	0.47	0.06	0.02	0.4	0.09	578.42	115	302.6	14.09	323.4	62.67	93.13
BW21-1-5-22	9.72	62.77	148.95	0.42	0.05	0.01	0.35	0.06	414.87	-90.19	306.28	10.02	295.65	40.89	96.53
BW21-1-5-23	1.57	11.36	35.83	0.32	0.05	0.01	0.37	0.11	646.1	-69.7	318.69	18.82	290.47	74.55	91.15
BW21-1-5-24	8.59	59.96	118.39	0.51	0.05	0.01	0.36	0.05	431.61	93.35	303.1	8.69	307.64	40.35	98.5
BW21-1-5-25	85.09	593.75	371.95	1.60	0.06	0	0.4	0.02	144.44	442.98	323.05	7.24	343.7	16.85	93.61
BW21-1-5-26	13.83	95.37	184.71	0.52	0.05	0.01	0.37	0.05	297.99	116.42	311.79	9.95	312.55	32.5	99.76
BW21-1-5-27	2.24	17.79	46.89	0.38	0.06	0.02	0.37	0.1	682.11	-188.4	296.88	14.11	292.83	67.86	98.64
BW21-1-5-28	4.38	29.58	59.76	0.50	0.06	0.01	0.35	0.08	395.3	492.7	305.16	16.26	292.88	55.23	95.98
BW21-1-5-30	4.37	33.69	69.86	0.48	0.05	0.01	0.35	0.06	324.55	200.1	297.98	12.66	295.24	42.65	99.08

注: Pb、铅; Th、钍; U、铀; ^{232}Th 、钍-232; ^{238}U 、铀-238; ^{235}U 、铀-235; ^{206}Pb 、铅-206; ^{207}Pb 、铅-207; σ 、相对标准偏差; $\pm\%$ 、相对误差。

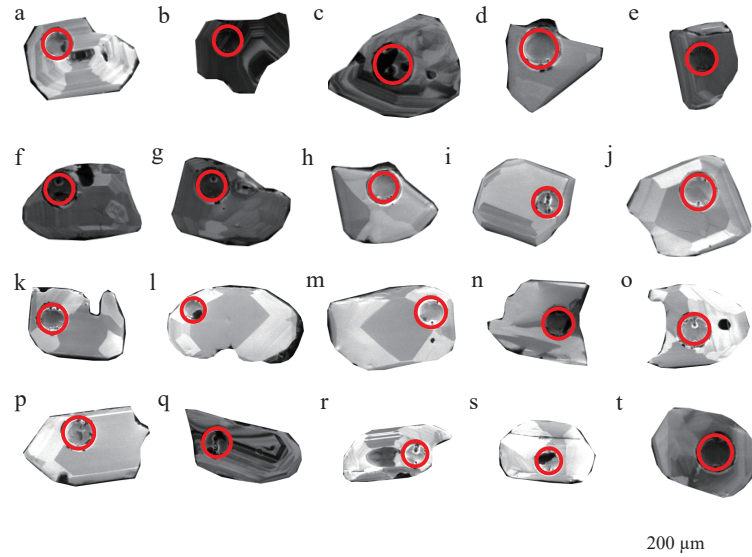


图3 准噶尔盆地西北缘克百断裂带百乌21井上石炭统成吉思汗山组代表性锆石阴极发光图像

Fig. 3 Cathodoluminescence (CL) images of representative zircons from the Upper Carboniferous Chengjisihanshan Formation (C_2c) in well Baiwu 21, Kebai fault zone, northwestern margin of the Junggar Basin

a—j. BW21-1样品,埋深1 523.3 m; a. BW21-1-1测点,年龄311.26 Ma; b. BW21-1-3测点,年龄315.58 Ma; c. BW21-1-6测点,年龄325.03 Ma; d. BW21-1-10测点,年龄308.82 Ma; e. BW21-1-12测点,年龄315.59 Ma; f. BW21-1-16测点,年龄308.60 Ma; g. BW21-1-21测点,年龄310.87 Ma; h. BW21-1-24测点,年龄316.74 Ma; i. BW21-1-26测点,年龄312.28 Ma; j. BW21-1-29测点,年龄324.18 Ma; k—o. BW21-15样品,埋深1 530.1 m; k. BW21-15-2测点,年龄316.69 Ma; l. BW21-15-6测点,年龄309.94 Ma; m. BW21-15-7测点,年龄316.73 Ma; n. BW21-15-12测点,年龄316.15 Ma; o. BW21-15-13测点,年龄310.67 Ma; p. BW21-15-14测点,年龄308.25 Ma; q. BW21-15-18测点,年龄309.60 Ma; r. BW21-15-23测点,年龄318.69 Ma; s. BW21-15-25测点,年龄323.05 Ma; t. BW21-15-26测点,年龄311.79 Ma

(图中红色圆圈表示锆石U-Pb年龄分析测点。)

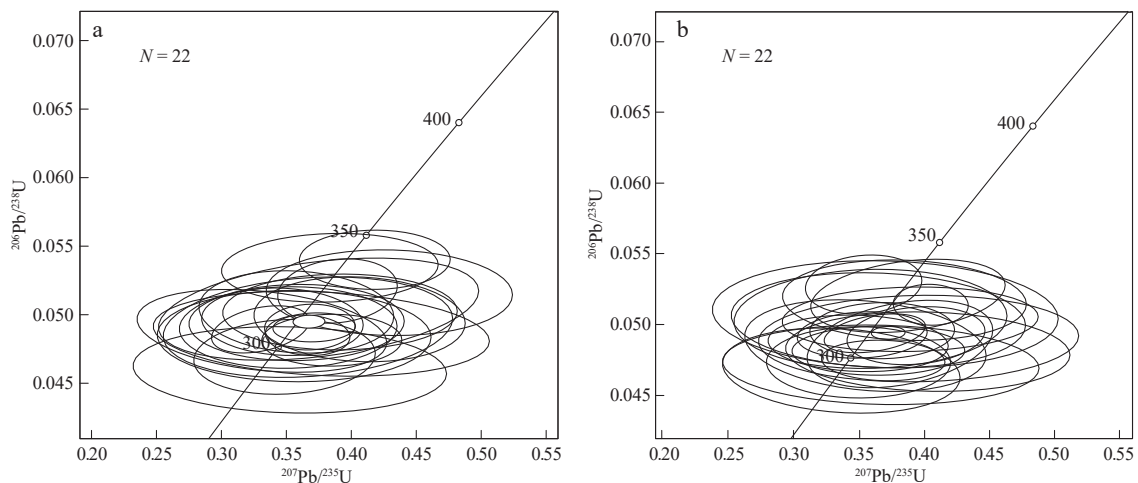


图4 准噶尔盆地西北缘克百断裂带百乌21井上石炭统成吉思汗山组凝灰质砂砾岩LA-ICP-MS锆石U-Pb同位素协和年龄图

Fig. 4 LA-ICP-MS zircon U-Pb concordia diagram for the tuffaceous sandy conglomerate of the Upper Carboniferous C_2c in well Baiwu 21, Kebai fault zone, northwestern margin of the Junggar Basin

a. 样本BW21-1协和年龄图; b. 样本BW21-15协和年龄图

($^{206}\text{Pb}/^{238}\text{U}$ 为铅-206同位素与铀-238同位素比值, $^{207}\text{Pb}/^{235}\text{U}$ 为铅-207同位素与铀-235同位素比值。)

山组的已发表年龄(315 ~ 310 Ma)高度吻合,为地层时代的重新厘定提供了精准的年代学约束。

在同一套地层中,位于百乌21井西北方向的百乌28井内,Wang等在该井的凝灰岩中获得了 $316.8 \text{ Ma} \pm$

1.7 Ma (MSWD = 1.15)的年龄数据^[52],该年龄代表了火山喷发年龄,并将其所在的火山岩夹层归属为成吉思汗山组。该年龄与本次研究在百乌21井凝灰质砂砾岩中获得的年龄一致。

3.3 地震剖面解释结果

通过合成记录完成井震标定后,对过百乌21井的两条连井剖面进行了系统解释。目标火山岩系在地震剖面上表现为中-弱振幅、中频、杂乱-断续反射的地震相特征,与上覆 P_1f 的中振幅、中频、中-高连续平行反射特征形成显著差异,二者之间为区域性的角度不整合面^[28]。同时,目标层系与下伏包古图组(C_1b)之间呈清晰的削截不整合接触关系,下伏地层的反射同相轴在不整合面之下发生明显的终止与削截,与区域上成吉思汗山组底界的不整合接触特征完全吻合。区域上,佳木河组在地震剖面上表现为中-强振幅、中-高连续的层状反射特征,与下伏石炭系呈超覆不整合接触

触,与上覆风城组整合或平行不整合接触,与本次目标层系的地震相特征和叠置关系存在根本性差异。

通过连井地震剖面的层位追踪,证实百乌21井的目标火山岩系可与西北方向百乌28井已厘定的成吉思汗山组进行区域对比,二者具有一致的地震相特征与地层叠置关系,构成了区域性分布的晚石炭世火山岩地层单元,从而否定了其属佳木河组局部分布的认识。

4 讨论

4.1 地层时代重新厘定

针对准噶尔盆地西北缘克百断裂带百乌21井原

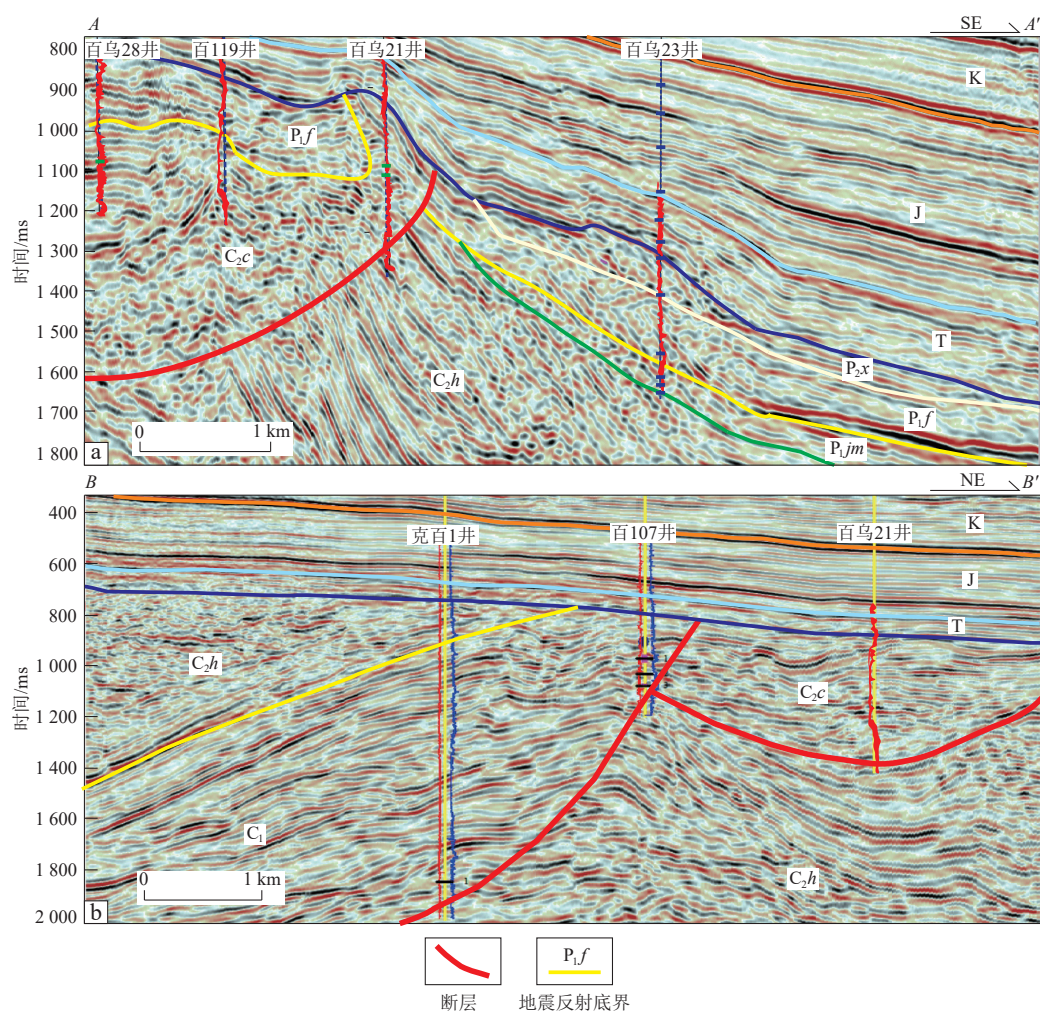


图5 准噶尔盆地西北缘克百断裂带成上石炭统成吉思汗山组百乌28井—百119井—百乌21井—百乌23井连井地震解释剖面(a)和克百1井—百107井—百乌21井连井地震解释剖面(b)(剖面位置见图1)

Fig. 5 Cross-well seismic interpretation sections of the Upper Carboniferous C2c in the Kebai fault zone, northwestern margin of the Junggar Basin: (a) across wells Baiwu 28, Bai 119, Baiwu 21, and Baiwu 23; (b) across wells Kebai 1, Bai 107, and Baiwu 21 (see Fig. 1 for the section location)

K. 白垩系; J. 侏罗系; T. 三叠系; P_{2x} . 上二叠统夏子街组; P_{1f} . 下二叠统风城组; P_{1jm} . 下二叠统佳木河组; C_{2h} . 上石炭统哈拉阿拉特组; C_{2c} . 上石炭统成吉思汗山组; C_1 . 下石炭统

划归佳木河组的火山岩系,本次研究基于高精度年代学、岩相学与地震资料的多维度约束,对其地层时代与归属进行了系统厘定。

1) 时代约束重新厘定研究区为成吉思汗山组地层。国际年代地层表中,石炭纪-二叠纪界线年龄为299.0 Ma,早二叠世的时间范围为299.0 ~ 272.0 Ma,本次研究获得的两件样品加权平均年龄为 $311.9 \text{ Ma} \pm 2.2 \text{ Ma}$ 和 $311.6 \text{ Ma} \pm 2.2 \text{ Ma}$,属于晚石炭世晚期,远早于早二叠世的时间范围,本次研究倾向于将该地层归属由佳木河组予以修改。同时,该年龄与区域上成吉思汗山组已发表的315.0 ~ 310.0 Ma的锆石U-Pb年龄在误差范围内完全一致,时代上与成吉思汗山组高度吻合。

2) 岩性-地球化学特征与成吉思汗山组高度匹配。在中拐地区佳木河组发育完整,与石炭系地层不整合接触,岩性为玄武岩、安山岩、凝灰岩、火山碎屑岩、流纹岩、砂砾岩、砂质泥岩等^[51]。本次研究的火山岩以基性-中性的玄武安山岩和安山岩为主,具有亚碱性、富钠贫钾特征,与成吉思汗山组上段火山岩的岩性组合完全一致。Wang对位于百鸟21井西北方向的百鸟28井的安山岩和玄武岩进行了地球化学分析,研究区火山熔岩具有亚碱性、富钠贫钾的特点,来源于亏损地幔^[65],与孙羽^[66]报道的准噶尔盆地西北缘地区成吉思汗山组的岩石地球化学特征相似,可能形成于弧后伸展构造环境,而不同于佳木河组以中-酸性火山岩为主的特点^[37]。

3) 地层接触关系与区域地层格架一致。地震剖面证实,该套地层与下伏包古图组地层呈角度不整合接触,此系成吉思汗山组最核心的区域识别标志——成吉思汗山组以区域性角度不整合覆盖于早石炭世弧盆体系地层之上,为准噶尔盆地西北缘晚石炭世造山作用后的第一个沉积盖层^[40]。而佳木河组作为早二叠世地层,其底界不整合于该套地层之上,二者分属两个不同的构造层序。

综合上述证据,本文将准噶尔盆地西北缘克百断裂带百鸟21井原划归下二叠统佳木河组的火山岩系,重新厘定为上石炭统成吉思汗山组,解决了该区长期存在的地层划分争议,完善了准噶尔盆地西北缘覆盖区晚古生代地层格架。

4.2 对准噶尔盆地西北缘古生代构造演化的约束

准噶尔盆地西北缘南部地区晚古生代构造演化的核心争议,在于古亚洲洋西段的闭合时限与构造体制转换过程,目前主要存在“晚石炭世闭合”与“早二叠世闭合”两种观点。本次研究获得312 Ma高精度火山岩年龄,为这一科学问题提供了新的年代学约束。

区域岩浆事件序列显示,准噶尔盆地西北缘地区晚古生代岩浆活动可分为3期:早石炭世(346 ~ 321 Ma)俯冲相关的弧岩浆作用、晚石炭世(318 ~ 300 Ma)伸展背景下的岩浆活动^[38]、早二叠世(295 ~ 270 Ma)后碰撞板内岩浆作用。本次研究的年龄为

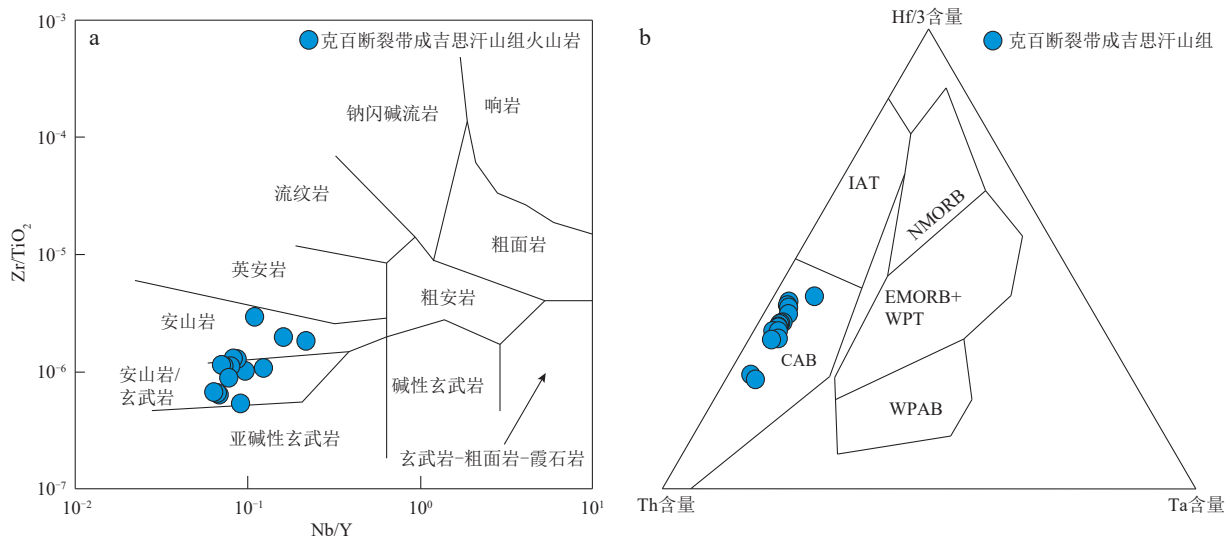


图6 准噶尔盆地西北缘克百断裂带上石炭统成吉思汗山组火山岩Nb/Y-Zr/TiO₂图解(a)和Th-Hf-Ta火山岩构造背景判别图图解(b)

Fig. 6 Nb/Y-Zr/TiO₂ diagram (a) and Th-Hf-Ta volcanic tectonic setting discrimination diagram (b) for volcanic rocks of the Upper

Carboniferous C_{2c} in the Kebai fault zone, northwestern margin of the Junggar Basin

Zr. 锆; TiO₂. 二氧化钛; Nb. 铌; Y. 钇; Hf/3. 铪/3; Th. 钍; Ta. 钽; IAT. 岛弧拉斑玄武岩; CAB. 岛弧钙碱性玄武岩; WPT. 板内拉斑玄武岩;

WPAB. 板内碱性玄武岩; EMORB. 富集型洋中脊玄武岩; NMORB. 正常洋中脊玄武岩

(图中所有样本均为成吉思汗山组钻井岩心,数据引自文献[52];a图据文献[68]修改;b图据文献[69]修改。)

结构,研究区 C_2c 地层主要受断层控制,据此圈定本次研究所追溯的成吉思汗山组地层分布范围(图7)。

成吉思汗山组火山岩储层之上直接覆盖着佳木河组和凤城组等烃源岩^[74-76],形成了良好的源储组合;同时,克百断裂带多期活动的断裂体系为油气垂向运移提供了通道,易形成构造-岩性复合油气藏。

5 结论

本文通过碎屑锆石 LA-ICP-MS 测年、岩石组合和地震剖面解释,对准噶尔盆地西北缘克百断裂带百乌21井原佳木河组火山岩进行了系统研究,得出以下主要认识:

1) 锆石 U-Pb 定年结果显示,百乌21井原划归为佳木河组的火山岩碎屑锆石 U-Pb 年龄分别为 $311.9 \text{ Ma} \pm 2.2 \text{ Ma}$ 和 $311.6 \text{ Ma} \pm 2.2 \text{ Ma}$,限定其形成时代为晚石炭世晚期,新归为成吉思汗山组。

2) 该套火山岩以杏仁状安山岩、玄武安山岩为主,具有亚碱性、富钠贫钾的地球化学特征,与区域上成吉思汗山组的特征一致,而与佳木河组存在明显差异。地震剖面证实其与下伏包古图组地层呈角度不整合接触,与区域上成吉思汗山组构造特征一致。

3) 本研究将克百断裂带原划归的佳木河组火山岩厘定为成吉思汗山组,解决了准噶尔地区地层划分争议。火山岩年龄为 $311.6 \sim 311.9 \text{ Ma}$,这限定了准噶尔盆地西北缘地区古亚洲洋西段的闭合时限应不晚于晚石炭世晚期,区域构造体制在 312.0 Ma 以前已从俯冲碰撞转换为后碰撞伸展,为中亚造山带西南段的构造演化提供了新约束。

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