河西走廊晚泥盆世地层中冥古宙碎屑锆石的发现*

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Abstract　Two detrital zircons with the age of 3.9Ga and 4.0Ga have been dated from Late Devonian strata in Hexi Corridor by LA-ICP-MS method. They are both magmatic zircons and the Th/U ratios are 1.01 and 0.58 respectively. Both zircons are enriched in heavy REE (HREE) compared to light REE (LREE) and show a distinctive positive Ce. The 4.0Ga zircon is with negative Eu while the 3.9Ga zircon without negative Eu. Using the geothermometer-^{49}Ti content of zircon, we calculated magmatic temperatures that were 792±36℃(3.9Ga) and 967±45℃(4.0Ga) respectively. The 3.9Ga zircon was analyzed for Hf-isotope: $^{176}Hf/^{177}Hf_i = 0.280169$, $\varepsilon_{Hf}(t) = -3.6$, $t_{DM} = 4139Ma$, $t_{DM}{}^C = 4319Ma$. It is the first report of the >3.9Ga zircons in Northwest China. The trace element characteristics of the zircons prove that the crust may exist on earth in the Hadean. Further, Combined with previous paleontological and paleomagnetic results, these results indicate that the Hexi Corridor might have the affinity with northwestern Australia in the Late Devonian.

Key words　Hadean; Detrital zircon; U-Pb age; Hf isotope; Trace element; Devonian; Hexi Corridor

摘　要　河西走廊地区晚泥盆统中宁组地层中，利用LA-ICP-MS法测年获得了3.9Ga和4.0Ga两颗碎屑锆石，其Th/U依次为1.01和0.58，均为岩浆锆石。两颗锆石稀土元素呈轻稀土(LREE)亏损、重稀土(HREE)富集，均具有Ce正异常，其中4.0Ga锆石具有Eu负异常，3.9Ga锆石无Eu负异常。利用锆石中^{49}Ti的含量计算原岩岩浆温度分别为792±36℃(3.9Ga)和967±45℃(4.0Ga)。3.9Ga锆石获得原位Hf同位素结果，$^{176}Hf/^{177}Hf_i = 0.280169$，$\varepsilon_{Hf}(t) = -3.6$，$t_{DM} = 4139Ma$，$t_{DM}{}^C = 4319Ma$。这两颗>3.9Ga碎屑锆石为西北地区首次发现，其微量元素特征说明在冥古宙时地球上可能存在地壳；结合前人古生物和古地磁研究结果，说明河西走廊在晚泥盆世时同澳大利亚西北部可能具有亲缘性。

关键词　冥古宙；碎屑锆石；U-Pb年龄；Hf同位素；微量元素；泥盆纪；河西走廊

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1 引言

冥古宙地球表层陆壳的形成是当今地球科学研究的热点之一,花岗质岩浆作用和早期陆壳再循环是地球早期陆壳演化的一个重要方面。然而,目前为止发现大于4.0Ga的岩石的报道很少,只有北美Acasta片麻岩为4.0Ga左右(Bowring *et al.*, 1984, 1989; Iizuka *et al.*, 2006, 2007)。地球上最老的锆石(4.4Ga)发现于西澳Jack Hills (Wilde *et al.*, 2001; Harrison *et al.*, 2005),该区域获得了大量>4.0Ga碎屑锆石的U-Pb年龄、Hf和O同位素结果(Maas *et al.*, 1992; Amelin, 1998; Peck *et al.*, 2001; Valley *et al.*, 2002; Cavosie *et al.*, 2004, 2005; Dunn *et al.*, 2005; Nemchin *et al.*, 2006; Ushikubo *et al.*, 2008; Kemp *et al.*, 2010; Bell *et al.*, 2011)。通过冥古宙岩石或锆石的研究,对我们了解地球早期陆壳的形成、演化历史和环境具有重要意义。

在我国一些前寒武纪基底也发现了古老锆石,如华北鞍山地区、冀东、信阳发现3.6~3.8Ga岩石和锆石(Liu *et al.*, 1992, 2008; Song *et al.*, 1996; Wan *et al.*, 2005; Zheng *et al.*, 2004; 刘敦一等, 1994; 吴福元等, 2005; 万渝生等, 2009),华南崆岭杂岩中发现≥3.5Ga岩石(Zhang *et al.*, 2006a)和3802±8Ma碎屑锆石($\varepsilon_{Hf}(t) = -0.8$, $t_{DM}^{1} = 3.96$Ga, $t_{DM}^{2} = 4.0$Ga)(Zhang *et al.*, 2006b),西北阿尔金山阿克塔什塔格变质岩中获得3605±43Ma单颗粒锆石U-Pb年龄(陆松年和袁桂邦, 2003; 李惠民等, 2001)。西藏普兰县石英片岩中发现锆石U-Pb年龄为4103±4Ma(多吉等, 2007);北秦岭西段奥陶纪火山岩中发现一颗4079±5Ma捕虏锆石(不谐和度2.28%)(王洪亮等, 2007),第五春荣等(2010)在该地区又发现两颗$^{207}Pb/^{206}Pb$年龄为4007±29Ma和3908±45Ma变质成因锆石。在华夏地块,发现Hf模式年龄大于4.0Ga的碎屑锆石较多,于津海等(2007)报道了潭溪片麻岩中3755Ma锆石Hf同位素模式年龄为4.07Ga, Yao *et al.* (2011)报道了赣南地区早古生代地层中两颗碎屑锆石Hf模式年龄分别为4068Ma(锆石U-Pb年龄2435±19Ma)和4202Ma(锆石U-Pb年龄2649±9Ma)。本文报道了河西走廊晚泥盆世地层中发现的3.6Ga、3.9Ga和4.0Ga三颗碎屑锆石,其中>3.9Ga这两颗锆石为西北地区首次发现;通过分析锆石原位微区Hf同位素和微量元素,对地球早期地壳形成、演化以及河西走廊地区在晚泥盆世古地理位置进行初步探讨。

2 地质背景与采样

研究区位于华北西缘河西走廊过渡带的东段(图1)。河西走廊过渡带为一早古生代的弧后盆地,归为阿拉善-龙首山地块的西南部大陆边缘(陆松年等, 2009)。该过渡带呈北西西-南东东向展布,其北界为龙首山断裂,断裂东延为

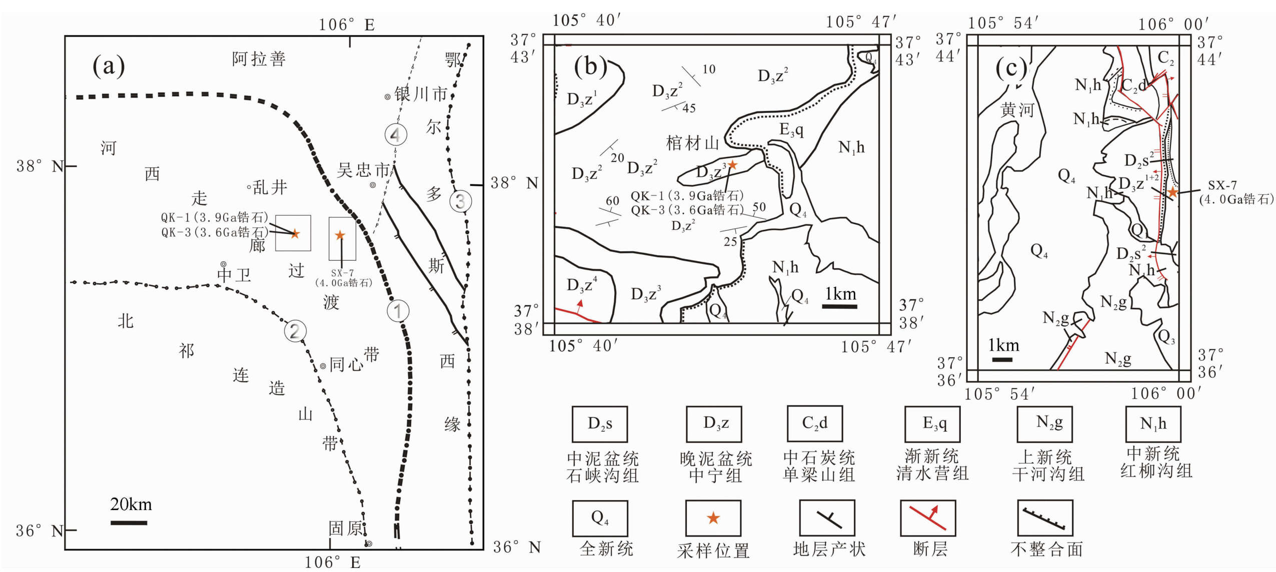

图1 河西走廊地质简图

(a):①龙首山-六盘山深断裂;②沙坡头-同心断裂;③车道-阿色浪断裂;④黄河断裂.(b):3.6Ga(样品号:QK-3)和3.9Ga(样品号:QK-1)碎屑锆石采样位置地质图.(c):4.0Ga碎屑锆石采样点地质图(SX-7为样品号)

Fig. 1 The simplified geological map of Hexi Corridor

(a): ① Longshoushan-Liupanshan fault; ② Shapotou-Tongxin fault; ③ Chedao-Aselang fault; ④ Huanghe fault; (b): The geological map for the sampling site of 3.6Ga detrital zircon (sample number: QK-3) and 3.9Ga detrital zircons (sample number: QK-1). (c): The geological map for the sampling site of 4.0Ga detrital zircons (sample number: SX-7)

元山子断裂,以后转为北西向的牛首山断裂和南北向的罗山断裂;南界可能为海原断裂带的月亮山,崛吴山断裂;东端与鄂尔多斯地块相接;西界可能为阿尔金断裂的东北延伸部分(Zhao *et al.*, 1993; 李清河等, 1999; Huang *et al.*, 2000; 陆松年等, 2009)。区内发育厚度很大的中-晚泥盆世河湖相沉积,为典型磨拉石建造(潘江等, 1987)。阿拉善-河西走廊地块是否为华北地块的西向延伸,是否与塔里木和柴达木地块构成西域板块,其大地构造属性尚存争议(葛肖虹和刘俊来, 2000)。

研究区上泥盆统中宁组整合接触覆于上泥盆统大岱沟组之上,与上覆地层中石炭统羊虎沟群或下石炭统臭牛沟组呈平行不整合接触;上泥盆统中宁组(D_3z)分三段:上段(D_3z^3)为浅湖相-深湖相泥岩、粉砂岩、砂质灰岩,灰岩,含丰富的鱼类化石;中段(D_3z^2)为浅湖相-河流相粉砂岩、砂岩;下段(D_3z^1)为河流相-浅湖相砂岩、粉砂岩(潘江等, 1987)。本次样品采自宁夏中宁地区晚泥盆统中宁组地层中(图2),为紫红色中粗粒长石石英砂岩。样品 QK-1(GPS 点为 37°40′46″N; 105°44′15.1″E)、QK-3(GPS 点为 37°40′47.2″N; 105°44′17.3″E)采集于上泥盆统中宁组上段,SX-7(GPS 点为 37°39′16.2″N; 105°59′38.0″E)采集于上泥盆统中宁组中段。样品 QK-3 中发现了 U-Pb 年龄为 3.6Ga 碎屑锆石,QK-1 中发现了 U-Pb 年龄为 3.9Ga 碎屑锆石;SX-7 中发现了 U-Pb 年龄为 4.0Ga 碎屑锆石。

3 测试方法

锆石是将所采砂岩样品粉碎至 60 目以下,按磁选和重液方法分选,最后在双目镜下挑纯。按照随机原则,每个样品粘 300~400 颗锆石,固定于环氧树脂中,经抛光后,进行透射光和反射光照相,并用阴极发光(CL)扫描电子显微镜进行图像分析,以观察锆石的抛光面及内部结构。CL 显微照相在西北大学大陆动力学国家重点实验室完成,CL 发光仪为加载于扫描电子显微镜(Quanta 400 FEG)上的美国 Gatan 公司的 Mono CL3+型阴极荧光探头,分析电压为 10kV,电流为 240μA。

锆石 U-Pb 年龄分析是在中国科学院地质与地球物理研究所多接收等离子质谱仪实验室利用激光剥蚀电感耦合等离子体质谱仪(LA-ICP-MS)上完成的。激光束斑直径为 32μm,频率为 8Hz,能量密度为 $15J/cm^2$。采用 91500 标准锆石(1062.4±0.6Ma)作为标准, GJ-1 (608.53±0.37Ma)作为未知样品对测试结果进行监控,采用美国国家标准物质局研制的人工合成硅酸盐玻璃 NIST610 为外标(Pearce *et al.*, 1997),^{29}Si 为内标进行元素含量校正。每个样品在试验开始和结束时分别测试两次 91500 和 NIST610,每完成 10 个测点加测一次 GJ-1 和 91500,每完成 20 个测点加测一次 NIST610。利用 Glitter (4.0 版) 软件处理测试数据,采用 Isoplot 程序(3.0 版)计算年龄,绘制谐和图(Ludwig,2003)。

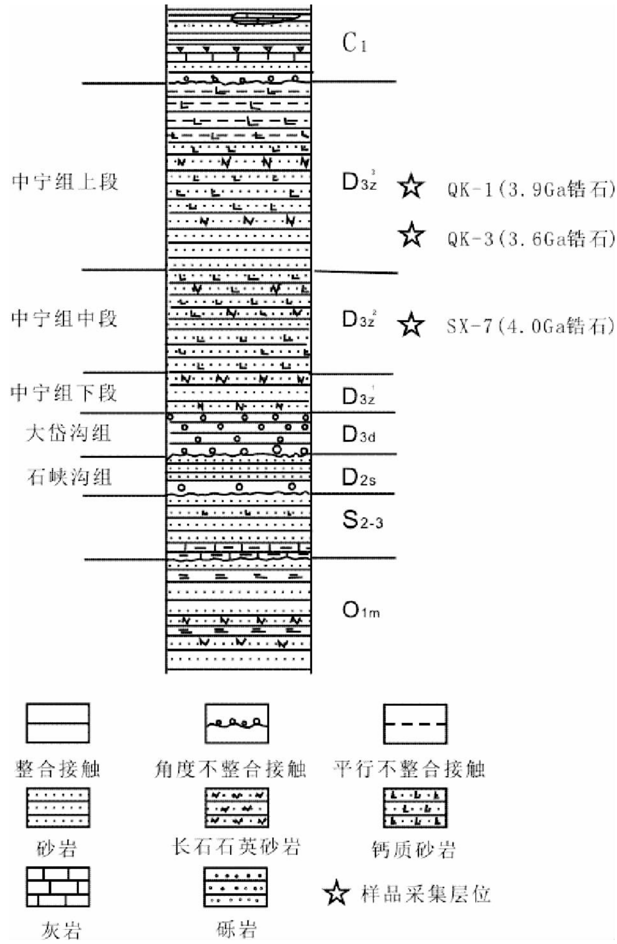

图 2 采样剖面地层柱状图

Fig. 2 Strata histogram for sampling profile

详细分析流程见谢烈文等(2008)、Xie *et al.* (2008)。

锆石原位 Lu-Hf 同位素分析在中国科学院地质与地球物理研究所 193nm 激光取样系统的 Neptune 多接收电感耦合等离子质谱仪(LA-MC-ICPMS)上进行,激光束斑直径为 60μm,激光脉冲宽度为 15ns,采用 He 气做为剥蚀物质载气,详细分析流程见 Wu *et al.* (2006)和 Xie *et al.* (2008)。每个样品在开始和结束分别测试两次 GJ-1,每完成 10 个测点加测一次 GJ-1。本次标样 GJ-1 的测定结果为 $^{176}Hf/^{177}Hf$ = 0.282009±25(2σ, N=145),该值与目前已获得的值在误差范围内一致(Elhlou *et al.*, 2006; Armin *et al.*, 2007)。$\varepsilon_{Hf}(t)$ 和模式年龄计算中,^{176}Lu 衰变常数为 1.867×10^{-11} (Bouvier *et al.*, 2008),现今球粒陨石的 $^{176}Lu/^{177}Hf$ 和 $^{176}Hf/^{177}Hf$ 分别为 0.0332、0.282772 (Bicher-Toft *et al.*, 1997),亏损地幔的 $^{176}Lu/^{177}Hf$ 和 $^{176}Hf/^{177}Hf$ 采用 0.0384、0.28325 (Griffin *et al.*, 2000),地壳模式年龄(t_{DM}^{C})采用平均地壳的 $^{176}Lu/^{177}Hf$=0.015 (Griffin *et al.*, 2002)。

借助锆石透射光、反射光、CL 照片,避开包裹体,确定测点位置,获得较准确可靠的年龄。测试 U-Pb 年龄时,每个样品在靶上从左往右,无论大小(>32μm)依次测试,直到锆石

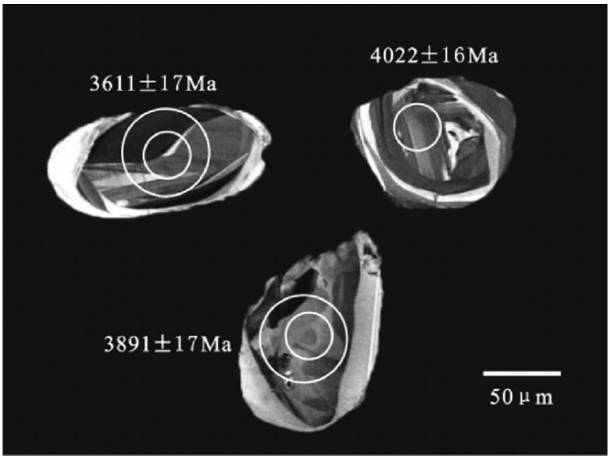

图3 锆石CL照片

大圆圈表示Hf同位素测试点;小圆圈表示U-Pb年龄测试点

Fig. 3 CL images of zircons

Large circles indicate positions for Hf-isotope analyses; small circles indicate positions for U-Pb age analyses

数目达到140或150为止。

4 锆石形态和U-Pb年龄

对三个样品测定约450颗锆石后,发现大量前寒武纪碎屑锆石(0.5~4.0Ga),峰值主要集中在~2.3~2.5Ga、1.8~2.1Ga、0.8~1.2Ga和0.5Ga,并发现两颗始太古代锆石(3.6Ga和3.9Ga)和一颗冥古宙锆石(4.0Ga)。^{207}Pb/^{206}Pb年龄为3611±17Ma的锆石U-Pb年龄谐和度达95%,无色透明,长150μm,宽75μm,CL照片显示锆石呈面状结构、较暗,具有变质增生亮边(图3),Th/U=0.14(表1)。^{207}Pb/^{206}Pb年龄为3891±17Ma的锆石U-Pb年龄谐和度达96%,无色透明,长150μm,宽95μm,CL照片显示锆石没有振荡环带结构,较暗,具有变质增生亮边(图3),Th/U=1.01(表1),为岩浆锆石。^{207}Pb/^{206}Pb年龄为4022±16Ma的锆石年龄谐和度为100%,无色透明,直径100μm左右,磨圆较好,CL照片显示核部具有明显的振荡环带结构(获取U-Pb年龄的位置),较亮,从CL照片观察应存在至少4期变质增生边(图3),Th/U=0.58(表1),为岩浆锆石。

5 锆石Hf同位素和微量元素

U-Pb年龄为3.9Ga的锆石获得原位Hf同位素结果:^{176}Hf/^{177}Hf$_i$ = 0.280169, $\varepsilon_{Hf}(t)$ = 3.6, t_{DM} = 4139Ma, $t_{DM}{}^{C}$ = 4319Ma(表2);^{207}Pb/^{206}Pb年龄为3611±17Ma锆石的原位Hf同位素结果为:^{176}Hf/^{177}Hf$_i$ = 0.280196, $\varepsilon_{Hf}(t)$ = 9.3, t_{DM} = 4113Ma, $t_{DM}{}^{C}$ = 4464Ma(表2)。这两颗锆石原位Hf同位素结果与华北板块3.8Ga左右岩石中锆石的Hf同位素结果

表1 锆石U-Pb同位素LA-ICP-MS分析结果

Table 1 Zircon LA-ICP-MS U-Pb isotopic data

Spots	Th	U	Th/U	Pb^{207}/Pb^{206}		Pb^{207}/U^{235}		Pb^{206}/U^{238}		Pb^{208}/Th^{232}		Pb^{207}/Pb^{206}		Pb^{206}/U^{238}		Pb^{207}/U^{235}		Pb^{208}/Th^{232}		con.
	($\times10^{-6}$)	($\times10^{-6}$)		Ratio	1σ	Ratio	1σ	Ratio	1σ	Ratio	1σ	Age(Ma)	1σ	Age(Ma)	1σ	Age(Ma)	1σ	Age(Ma)	1σ	
19-106	17.3	124.4	0.14	0.3287	0.0036	31.8073	0.3168	0.7019	0.014	0.1992	0.0031	3611	17	3428	53	3544	10	3672	53	95%
19B-073	137.5	136.4	1.01	0.3952	0.0046	42.7165	0.462	0.784	0.0162	0.1414	0.0024	3891	17	3732	58	3836	11	2673	42	96%
8-090	164	281.8	0.58	0.4314	0.0047	51.5496	0.5336	0.8667	0.0183	0.2282	0.0035	4022	16	4024	63	4023	10	4155	57	100%

表2 锆石Hf同位素组成

Table 2 Zircon Hf isotopic compositions

Spots	Age (Ma)	$^{176}Yb/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	2σ	$^{176}Hf/^{177}Hf_i$	$\varepsilon_{Hf}(0)$	$t_{Hf}(t)$	t_{DM}(Ma)	$t_{DM}{}^{C}$(Ma)	$f_{Lu/Hf}$
19-106	3611	0.029556	0.001084	0.280272	0.000022	0.280196	-88.4	-9.3	4113	4464	-0.97
19B-073	3891	0.025122	0.000805	0.280229	0.000014	0.280169	-89.9	-3.6	4139	4319	-0.98

表3 锆石稀土元素及^{49}Ti温度计

Table 3 Zircon REE and geothermometer-^{49}Ti content

Spot	U-Pb Age	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	^{49}Ti	^{49}Ti温度计	误差
	(Ma)								($\times10^{-6}$)								(℃)	(℃)
19B-073	3891	0.259	12.94	0.976	18.45	64.41	39.8	285.7	80.33	638.84	142.76	372.54	52.26	339.31	37.26	15.93	792	±36
8-090	4022	0.101	11.3	0.291	4.94	11.52	2.09	68.7	25.43	304.04	110.43	450.39	93.97	886.19	117.61	68.70	967	±45

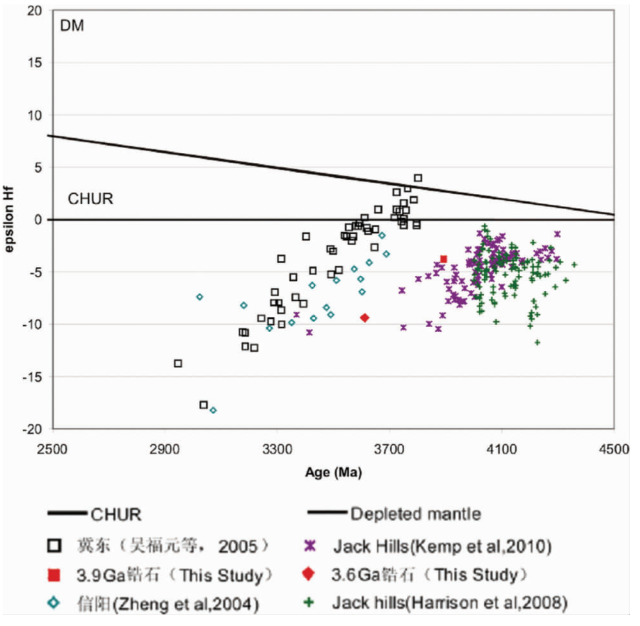

图 4 锆石 $\varepsilon_{Hf}(t)$ 对 U-Pb 年龄图解

Fig. 4 $\varepsilon_{Hf}(t)$ vs. U-Pb age for zircons

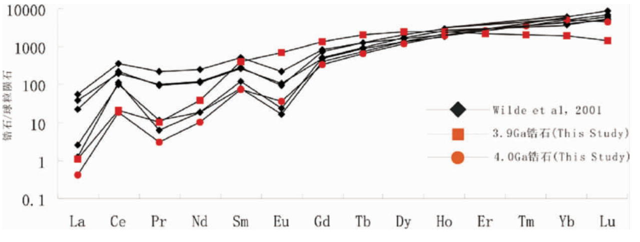

图 5 冥古代锆石稀土元素蛛网图

Fig. 5 Rare earth element patterns of Hadean zircon

（吴福元等，2005；Zheng *et al.*，2004）存在明显不同，而与 Jack Hills > 4.0Ga 锆石的 Hf 同位素特征（Kemp *et al.*，2010；Harrison *et al.*，2008）非常相近（图 4）。

锆石稀土元素轻稀土（LREE）亏损重稀土（HREE）富集，均具有 Ce 正异常，4.0Ga 锆石具有 Eu 负异常，3.9Ga 锆石没有 Eu 负异常（图 5）。Ce 正异常是 Ce^{+4} 优先进入锆石晶格的结果（吴元保等，2003），Eu 负异常则是锆石与长石平衡生长的结果（Rubatto and Williams，2000）。

利用锆石中 ^{49}Ti 含量计算母岩岩浆温度（Ferry and Watson，2007），3.9Ga、4.0Ga 锆石的母岩岩浆温度分别为 792 ± 36℃ 和 967 ± 45℃（表 3）。

6 地质意义

6.1 早期陆壳生长

古老锆石的发现和研究可有效追溯冥古宙大陆地壳的形成。Jack Hills 地区 4.4Ga 左右碎屑锆石的稀土元素具有轻稀土亏损重稀土富集，Ce 正异常和 Eu 负异常（图 5），且测试点附近发现了 SiO_2 包裹体，表明这些锆石源于花岗岩岩浆（Wilde *et al.*，2001）。前人获得这些 40 亿以上锆石的 $\delta^{18}O$ 值为 6.3‰～7.5‰（Peck *et al.*，2001；Cavosie *et al.*，2006），而地幔平均 $\delta^{18}O$ 为 5.3 ± 0.3‰（Valley *et al.*，2005），说明在地球历史早期有大陆地壳的存在。Grimes *et al.*（2007）统计了大量的洋壳锆石和陆壳锆石的微量元素特征，通过 U 对 Yb、U/Yb 对 Hf 或 Y 图解很好地将陆壳锆石和洋壳锆石区分开来，Narryer Terrane 太古宙变质沉积岩中冥古宙碎屑锆石及 Acasta Gneiss 中的 4.2Ga 碎屑锆石在 U 对 Yb、U/Yb 对 Hf 或 Y 图解中明显处于大陆地壳区域（图 6），表明在地球形成早期可能有陆壳的存在。本文报道的 3.9Ga 和 4.0Ga 两颗锆石在 U/Yb 对 Hf 或 Y 图解中也落入到了大陆地壳区域（图 6），可能说明地球在冥古宙有地壳的存在。

6.2 构造意义

西藏普兰县石英片岩和北秦岭西段奥陶纪火山岩中冥古宙（碎屑或继承）锆石的发现（华南崆岭群，≥3.5Ga）并非偶然，其中西藏普兰变质沉积岩的老锆石与西澳 Jack Hills 冥古宙碎屑锆石（>4.0Ga）的沉积物源区可能具有成因联系（万渝生等，2009）。古地理和古地磁研究也均表明西藏

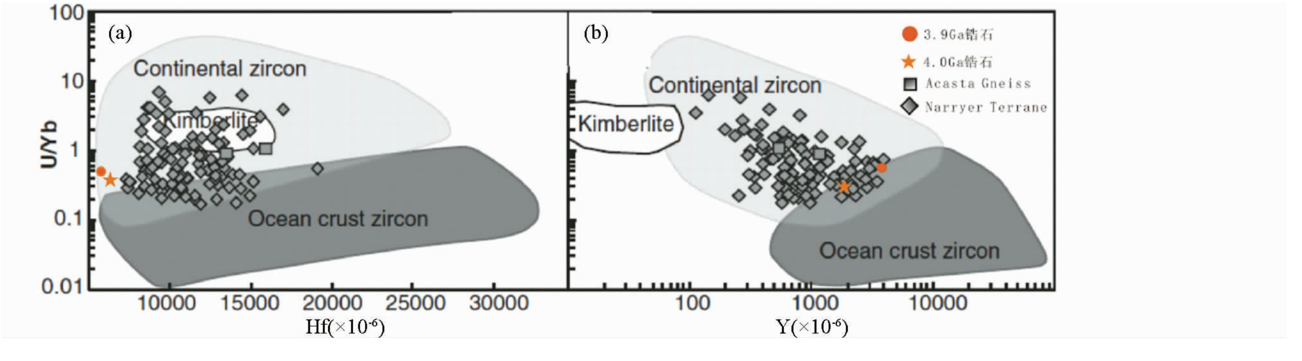

图 6 冥古宙锆石 Hf 对 U/Yb 图解（a）和 Y 对 U/Yb 图解（b）（据 Grimes *et al.*，2007 修改）

Fig. 6 Hf vs. U/Yb (a) and Y vs. U/Yb (b) for Hadean zircon (after Grimes *et al.*, 2007)

雅鲁藏布江带缝合带西段和华南地块与东冈瓦纳地块具有明显的亲缘关系(Allegre *et al.*, 1984; Yang *et al.*, 2004)。宁夏中宁地区晚泥盆世地层中发现的中华豆石介族(介形类),表明泥盆纪时该区属华南生物地理区系(王尚启等,1995);发现的胴甲鱼表明中宁与华南和澳大利亚西北部具有明显亲缘性(Jia *et al.*, 2010)。上述地区在古生代中期的亲缘关系也得到古地磁研究的初步证明(Huang *et al.*, 2000)。本次在中宁地区获得的3.6Ga和3.9Ga锆石同华北板块3.8Ga左右岩石中锆石Hf同位素特征亲缘性较差,同Jack Hills地区4.0Ga以上锆石Hf同位素具有一定的相似性,则说明河西走廊在晚泥盆世时与澳大利亚西北部沉积物源区可能具有成因联系。

7 结论

本次在河西走廊地区晚泥盆统中宁组地层中利用LA-ICP-MS法测年,首次在我国西北地区的沉积岩中发现3.9Ga和4.0Ga碎屑锆石。这两颗锆石的微量元素特征,说明在冥古宙时地球上可能存在地壳;3.9Ga锆石同Jack Hills地区>4.0Ga锆石Hf同位素具有一定的相似性,结合前人古生物和古地磁研究结果,说明在晚泥盆世时河西走廊同澳大利亚西北部可能具有亲缘性。

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