



辽东湾海域新元古界长龙山组石英砂岩物源特征及其地质意义

赵子霖, 周雪威, 李夔洲, 郭涛, 彭靖松, 侯明才

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辽东湾海域新元古界长龙山组石英砂岩物源特征及其地质意义

赵子霖¹,周雪威¹,李夔洲²,郭涛³,彭靖松³,侯明才^{1,2}

1. 成都理工大学沉积地质研究院&深时地理环境重建与应用自然资源部重点实验室,成都 610059

2. 油气藏地质及开发工程全国重点实验室(成都理工大学),成都 610059

3. 中海石油(中国)有限公司天津分公司,天津 300452

摘要 【目的】渤海辽东湾海域西南部钻井钻遇新元古界青白口系长龙山组石英砂岩,深入研究其物源特征,对华北克拉通太古代至元古代重大地质事件解剖具有重大意义。【方法】对采自BD4-1a井2 482 m附近的五件石英砂岩样品进行了全岩地球化学和碎屑锆石U-Pb年代学分析。【结果】全岩地球化学分析结果显示该石英砂岩具有较高的SiO₂含量(88.53%~93.06%),化学蚀变指数(CIA)值介于69.5~71.6,成分变异指数(ICV)值介于0.69~3.99,样品表现为高成分成熟度和结构成熟度、中等风化。Th/U值介于3.46~4.92,Cr/Zr值介于0.17~0.35,ΣREE值介于(8.26~24.12)×10⁻⁶,LREE/HREE值介于6.28~10.21,δEu值介于0.77~1.04,呈弱负异常。碎屑锆石U-Pb年龄分布于2 744~1 581 Ma,主要年龄峰值为~1 845 Ma,次要年龄峰值为~2 225 Ma、~2 340 Ma、~2 600 Ma和~2 725 Ma。【结论】全岩地球化学分析结果显示其物源主要来自于上地壳长英质岩石。2.7~2.5 Ga的碎屑锆石是华北克拉通陆壳生长事件及构造热事件形成的记录;2.2~1.8 Ga的碎屑锆石与华北克拉通东部陆块和西部陆块拼合形成同一结晶基底事件的时间相吻合,是哥伦比亚超大陆聚合事件的地质记录;而1.8~1.6 Ga的碎屑锆石年龄记录的应该是哥伦比亚超大陆裂解事件。

关键词 渤海;碎屑锆石;地球化学;物源;哥伦比亚超大陆

第一作者简介 赵子霖,男,1998年出生,硕士研究生,古地理重建,E-mail: zzzlzzl1225@163.com

通信作者 侯明才,男,教授,E-mail: houmc@cdut.edu.cn

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0 引言

随着激光剥蚀等离子质谱仪、高灵敏度高分辨率离子探针等技术的快速发展,碎屑锆石U-Pb测年在沉积盆地物源分析中得到广泛应用^[1-2]。锆石广泛存在于多种类型的岩石中,具有极强的稳定性,可以追溯碎屑岩的源区、地壳演化和岩浆活动等重要的地质信息^[3]。另外,碎屑沉积岩的微量元素、稀土元素等虽经历了风化、搬运和固结成岩等作用,但仍能很好地保存源区的信息,可以有效地恢复源区环境和母岩特征^[4-5]。因此,碎屑沉积岩的碎屑锆石U-Pb年代学和全岩地球化学综合分析,能够有效地判别

沉积物物源、岩浆事件及地壳演化等。

渤海海域潜山油气资源丰富,近几年针对元古界的潜山油气勘探取得重大突破,例如,渤中19-6、渤中13-2等深层变质岩/火山岩潜山大型油气藏^[6-7],为京津冀能源资源供应提供了保障。与之相关的沉积盆地演化与恢复、变形过程、源-汇系统等是油气勘探的基础地质问题。本文以渤海辽东湾海域西南部BD4-1a井钻遇的石英砂岩岩心为研究对象,开展碎屑锆石U-Pb年代学和全岩地球化学分析,并结合海域周缘相关的研究成果,探讨了青白口系长龙山组石英砂岩的物源特征和蕴含的构造地质学意义。

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1 地质背景和样品概述

1.1 地质背景

华北克拉通由渤海湾盆地、鄂尔多斯盆地、南华北盆地、沁水盆地和吕梁—太行山等组成(图1a),是中国重要的构造单元,其基底由东部陆块、西部陆块、中央造山带和胶—辽—吉造山带构成^[11-12]。渤海海域位于华北克拉通渤海湾盆地东部,是一个几近于封闭的内海,根据地形地貌可分为辽东湾、渤海湾、莱州湾、中央浅海盆地和渤海海峡五部分^[12]。辽东湾地区位于渤海海域东北部,是渤海湾断陷盆地最北缘的一个拗陷^[13],从构造格局可分为两隆三凹,由西向东分别是辽西凹陷、辽西凸起、辽中凹陷、辽东凸起和辽东凹陷(图1b)。盆地地势呈现出西高东低,北高南低的特征^[15-16]。

1.2 样品概述

BD4-1a井位于渤海辽东湾地区辽西凹陷,该井钻遇新近系馆陶组、古近系东营组陆源碎屑岩、奥陶系灰岩和粉晶白云岩以及底部青白口系长龙山组的一套石英砂岩(图2a)。此次在BD4-1a井2482 m附近采集了5件石英砂岩样品,样品编号分别为2482-1、2482-2、2482-3、2482-4和2482-5,对所有样品进行了全岩元素地球化学分析,同时对2482-3号样品进行了锆石U-Pb测年。

获得BD4-1a井样品的岩心手标本风化面呈黄褐色、土黄色,中粗粒结构,块状构造(图2b)。正交偏光下可见具有砂状结构,颗粒粒径为0.3~0.7 mm,颗粒支撑、接触式胶结。矿物分选性良好,磨圆度呈次

圆状—圆状,石英含量极高(约90%),可能发生过较远距离的搬运。视域内有少量岩屑和杂基,压溶作用不强,硅质胶结物含量较高,石英普遍存在次生加大边(图2c)。

2 测试方法

2.1 全岩地球化学

渤海辽东湾地区石英砂岩样品的全岩主量、微量元素分析在武汉上谱分析科技有限责任公司完成。全岩主量元素测试采用仪器为日本理学Primus II X射线荧光光谱仪(XRF),将样品在105℃烘干后称取约1.0 g计算烧失量;使用无水 $\text{Li}_2\text{B}_4\text{O}_7$ 为助熔剂, NH_4NO_3 为氧化剂制成玻璃片进行XRF测试。全岩微量元素测试采用电感耦合等离子体质谱仪Agilent 7700e ICP-MS分析完成,将称取的50 mg样品粉末放在Teflon溶样弹中,依次加入HF和 HNO_3 后置于烘箱中在(约190℃)加热24 h以上,使样品全溶;使用1 mL内标In(浓度为 1×10^{-6})再次处理;最后将溶液转入聚乙烯料瓶,并用2% HNO_3 稀释至100 g后进行ICP-MS测试。

2.2 碎屑锆石

锆石的挑选、制靶和CL照相在南京宏创地质勘查技术服务有限公司完成。本次石英砂岩样品共测试135颗碎屑锆石,U-Pb定年在油气藏地质及开发工程国家重点实验室(成都理工大学)完成,实验设备为美国应用光谱公司Resolution LR 193nm激光剥蚀系统和美国安捷伦7900质谱仪。此次分析中,激光能量密度为 3.5 J/cm^2 ,束斑直径 $29 \mu\text{m}$,频率8 Hz,

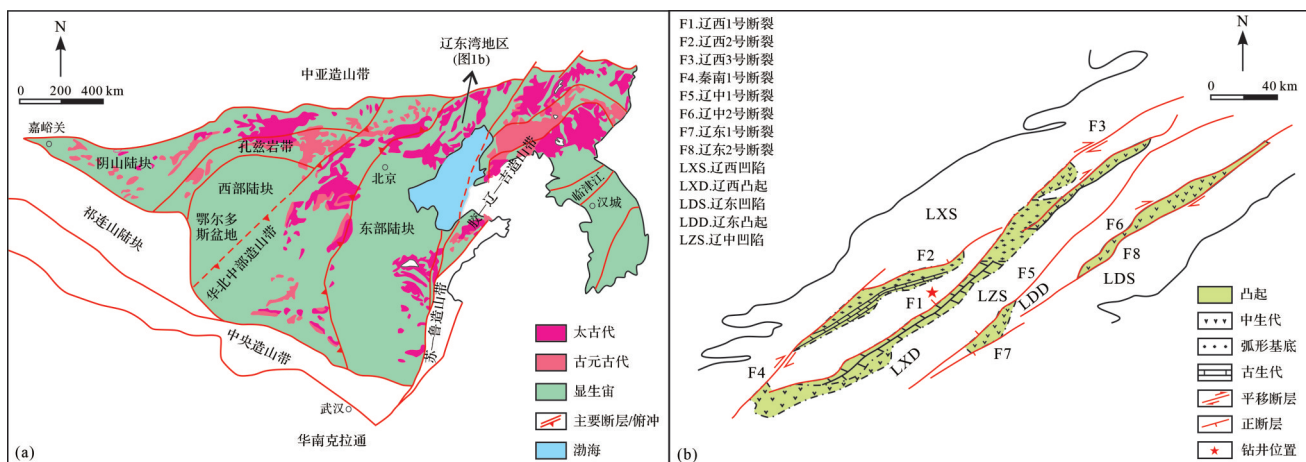


图1 (a)华北克拉通大地构造简图(据文献[8-9]修改);(b)辽东湾地区构造简图(据文献[14]修改)

Fig.1 (a) Tectonic sketch of the North China Craton (modified from references [8-9]); (b) structural sketch of the Liaodong Bay area (modified from reference [14])

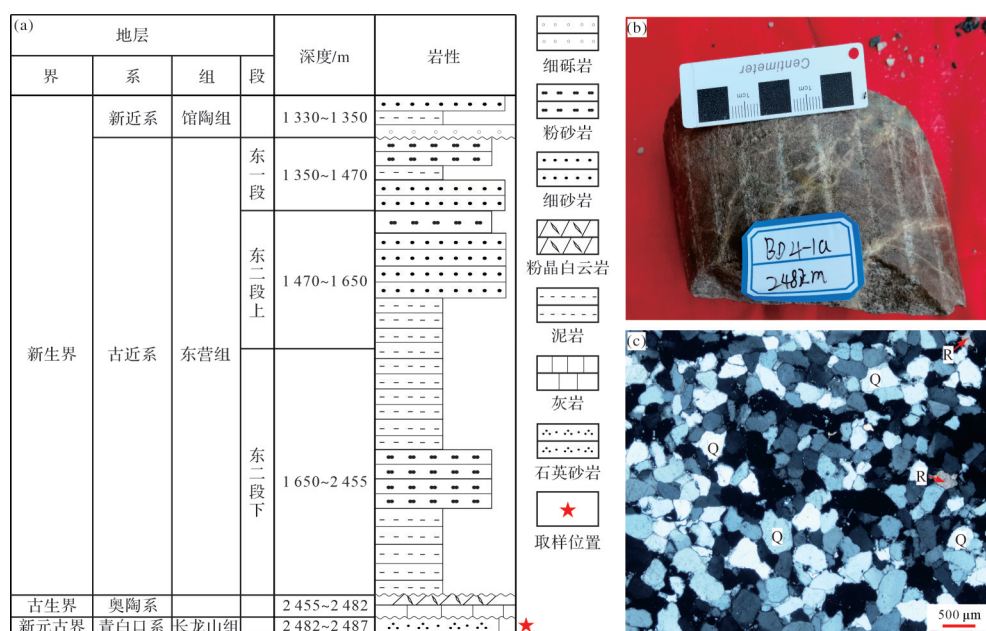


图2 (a)地层柱状图;(b)BD4-1a井2482 m岩心;(c)石英砂岩显微照片(Q.石英;R.岩屑)

Fig.2 (a) Columnar section of stratum; (b) 2482 m core of well BD4-1a; (c) the microscopic photograph of quartz sandstone (cross-polarized light; Q. quartz; R. rock fragment)

剥蚀45 s;以标准锆石91500为外标,校正仪器质量歧视和元素分馏;以标准锆石PLE为盲标,检验数据质量;使用NIST SRM610为外标、Si为内标,标定锆石微量元素含量。对分析数据的离线处理采用软件ICPMSDataCal^[17]完成。利用Isoplot/Ex_ver3^[18]对锆石样品的U-Pb年龄谱和图绘制和年龄加权平均计算。

3 测试结果

3.1 全岩地球化学

3.1.1 主量元素

全岩地球化学分析结果显示,石英砂岩SiO₂质量分数介于88.53%~93.06%,平均值为91.46%;Al₂O₃质量分数介于2.02%~3.73%,平均值为2.45%;TF₂O₃的质量分数介于0.47%~1.60%,平均值为1.03%;MgO质量分数介于0.21%~0.96%,平均值为0.54%;CaO质量分数介于0.12%~2.16%,平均值为1.03%;Na₂O质量分数较低,介于0.03%~0.05%,平均值为0.04%;K₂O的质量分数介于0.68%~1.23%,平均值为0.81%。

3.1.2 微量元素

沉积岩中的稀土元素(Rare Earth Element, REE)特征主要受控于物源区类型和沉积作用过程,风化作用与成岩作用对其影响因素很小,因此可以通过稀土元素的相关信息来判断物源的沉积特征^[19-20]。本次石英砂岩样品ΣREE的含量介于(8.26~24.12)×10⁻⁶,平

均值为12.54×10⁻⁶;LREE/HREE比值介于6.28~10.21,平均比值为7.98;δEu值介于0.77~1.04,平均值为0.89,呈弱负异常;δCe值介于0.94~1.01,平均值为0.98,基本无异常。样品球粒陨石标准化图解可见折线整体轻微右倾,轻稀土相对富集,重稀土相对亏损(图3a)。微量元素原始地幔标准化蛛网图显示5件样品总体变化趋势基本一致,Rb、Pb和Hf富集,Ta、P和Ti亏损(图3b)。

3.2 碎屑锆石年龄

对2482-3号石英砂岩样品共选取135颗碎屑锆石进行U-Pb定年分析,样品中的碎屑锆石形态多呈次圆状和圆状,锆石长度介于70~210 μm,长宽比介于2:1~1:1(图4)。135颗碎屑锆石中Th/U的值均大于0.1,结合锆石阴极发光图分析,认为此次研究的锆石均为岩浆锆石^[23]。

将谐和度大于95%的视为有效数据,其中,本次测试有126颗锆石谐和度大于95%(除编号为S-23、S-35、S-41、S-45、S-46、S-47、S-52、S-60、S-104九颗锆石外)。²⁰⁷Pb/²⁰⁶Pb年龄介于2744~1581 Ma,元古宙碎屑锆石最多(112颗),其次为新太古代(12颗),仅有2颗为中元古代。锆石年龄频谱图显示本次石英砂岩样品中存在5个显著峰值,对应的年龄分别为~1845 Ma、~2225 Ma、~2340 Ma、~2600 Ma和~2725 Ma(图5b)。

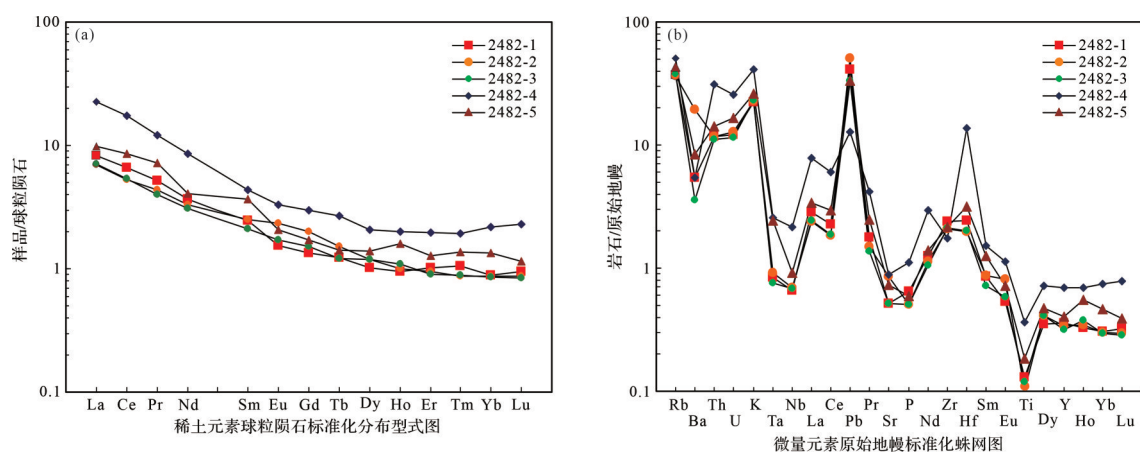


图3 (a) 稀土元素球粒陨石标准化分布图(标准化数据引自文献[21]); (b) 微量元素原始地幔标准化蛛网图(标准化数据引自文献[22])

Fig.3 (a) Chondrite-normalized rare earth element chondrites (chondrite data from reference [21]); (b) primitive mantle-normalized spider diagram (primitive mantle data from reference [22])

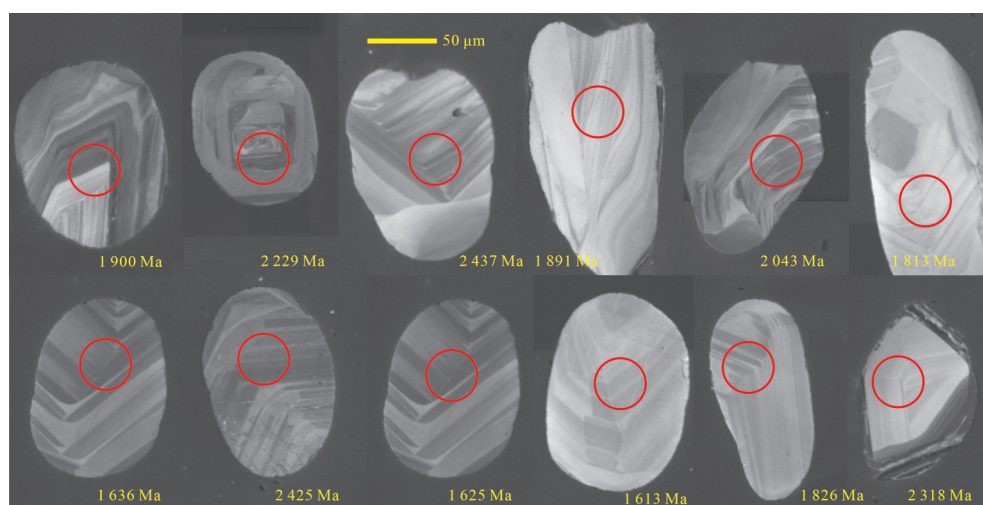


图4 渤海辽东湾地区石英砂岩碎屑锆石阴极发光(CL)图像及年龄

Fig.4 Cathodoluminescence image and the age of the detrital zircon from quartz sandstones in Liaodong Bay, Bohai Sea

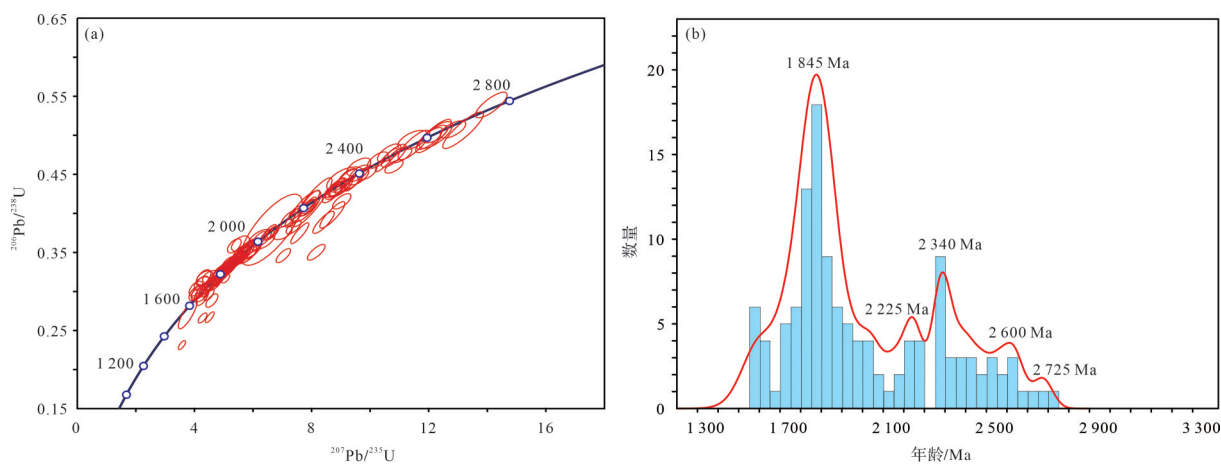


图5 (a) 石英砂岩样品碎屑锆石 U-Pb 年龄谐和图; (b) 石英砂岩样品碎屑锆石 U-Pb 年龄分布直方图

Fig.5 (a) Detrital zircon U-Pb age concordia diagram and (b) age distribution histogram of quartz sandstone samples

4 讨论

4.1 物源分析

4.1.1 碎屑锆石定年对物源的启示

如前所述,由钻井资料可以得出该套石英砂岩的沉积时代不晚于奥陶纪,通过对渤海湾盆地地层对比研究发现,渤海湾盆地寒武纪主要为碳酸盐岩^[24-25],因此该套石英砂岩应为前寒武纪地层。渤海湾盆地前寒武系发育石英砂岩的地层主要为新元古代长龙山组和中元古代常州沟组^[26-27],本文统计了长龙山组和常州沟组碎屑锆石年龄研究成果,与本次石英砂岩的碎屑锆石年龄分布进行了对比(图6)。

任荣等^[28]研究发现北京昌平地区长龙山组碎屑锆石年龄分布于3 372~1 644 Ma,主要年龄峰值为~1 800 Ma,次要年龄峰值为~2 510 Ma、~2 400 Ma、~2 270 Ma、~1 955 Ma(图6b);Wan *et al.*^[29]在北京十三陵地区长龙山组获得的碎屑锆石年龄分布于2 931~1 800 Ma,主要年龄峰值为~1 830 Ma,次要年龄峰值为~2 765 Ma、~2 487 Ma、~2 370 Ma(图6c);王振涛等^[30]认为河北怀来龙凤山地区长龙山组碎屑锆石年龄分布于2 931~1 573 Ma,主要年龄峰值为~1 824 Ma(图6d)。任荣等^[28]发现的北京昌平地区常州沟组的碎屑锆石年龄分布于2 680~1 885 Ma,主要年龄峰值为~2 490 Ma,次要年龄峰值为~2 530 Ma(图6e);Wan *et al.*^[29]报道的北京十三陵地区常州沟组的碎屑锆石年龄分布于2 745~1 775 Ma,主要年龄峰值为~2 522 Ma,其他次要年龄峰值为~2 483 Ma、~2 405 Ma(图6f)。

本次辽东湾地区石英砂岩中的碎屑锆石年龄分布于2 744~1 581 Ma,主要年龄峰值为~1 845 Ma,还有其他多个次级年龄峰值:~2 725 Ma、~2 600 Ma、~2 340 Ma和~2 225 Ma(图6a)。通过与邻区碎屑锆石分析对比发现,此次样品与长龙山组都存在1 800~1 850 Ma的主要峰值,同时存在~2 600 Ma和~2 300 Ma等次要峰值,二者的碎屑锆石年龄峰值基本一致(图6a~d)。常州沟组普遍存在的主要峰值为~2 500 Ma,为单峰形式,而本次石英砂岩中碎屑锆石和长龙山组都具有明显的双峰式。综上所述,BD4-1a井潜山石英砂岩中的碎屑锆石年龄与长龙山组相似度很高,具有相同的物源;综合钻井资料及区域地层对比研究判断,其与青白口系长龙山组为同一套地层。

在华北克拉通北部的辽宁地区发现了大量的岩浆岩体,例如辽宁曹庄地区年龄为2 550~2 529 Ma的富钾花岗岩^[31]、辽宁鞍山地区年龄为~2 527 Ma的斜长片麻岩和~2 536 Ma的闪长岩^[32]、辽宁牧牛河地区年龄为~2.18 Ga的I型和A₂型花岗岩^[33]等,指示辽宁地区存在的岩浆岩体是青白口系长龙山组的直接物源。华北克拉通东部的河北地区陆续报道了许多岩浆岩年龄,例如河北东部年龄为~2 546 Ma和~2 510 Ma的花岗片麻岩^[34]、河北兴山地区年龄为2.6~2.5 Ga的片麻岩^[35]、河北西北部宣化地区年龄为~1 856 Ma的角闪岩^[36]和年龄为1 872 Ma的麻粒岩^[37]等,暗示着河北地区的岩浆岩体可能为青白口系长龙山组的直接物源之一。

4.1.2 全岩地球化学对物源的启示

碎屑岩的地球化学特征不仅能够反映物源区的岩石成分,而且能够反映沉积构造背景^[38]。Nesbitt *et al.*^[4]提出了CIA指数概念,它可以定量地反映物源区风化程度。Liu *et al.*^[39]认为,当CIA的值大于80时为强化学风化;当CIA的值为60~80时为中等强度化学风化;当CIA的值为55~60时为弱化学风化;若CIA值小于55,风化类型则主要为机械风化。本次渤海辽东湾地区石英砂岩样品的CIA值介于69.5~71.6,平均值为71。据A-CN-K图解可见样品均更靠近Al₂O₃一端,说明该区域砂岩经历了较强的化学风化作用,含有Al₂O₃的黏土型矿物富集,CaO、Na₂O和K₂O等淋滤丢失(图7a)^[40-41]。ICV指数主要用来衡量沉积物质的再循环,当ICV指数大于1时,指示该样品黏土矿物含量较少,可能为构造活动地带首次沉积;而ICV指数小于1时,则表明样品的黏土矿物含量较高,可能为经历了再沉积的产物^[42-43]。本次样品的ICV值介于0.69~3.99(平均值为2.21),在ICV-CIA图解上可见绝大部分样品为不成熟的中等风化(图7b)^[4]。

本次样品中Th/U变化范围为3.46~4.92(平均值为3.98),上地壳平均值为3.8;La/Sc变化范围为1.84~4.12(平均值为2.64),上地壳平均值为2.73;Th/Sc变化范围为1.12~2.04(平均值为1.40),上地壳平均值为0.97;本次石英砂岩样品值与上地壳值十分接近^[44]。在La/Yb-La/Th图解中石英砂岩样品点均落在上地壳附近^[45](图8a)。沉积物中Cr/Zr的值能够反映长英质岩石在物源的参与度^[46],本文样品的Cr/Zr的值介于0.17~0.35(平均值为0.24),比值远小

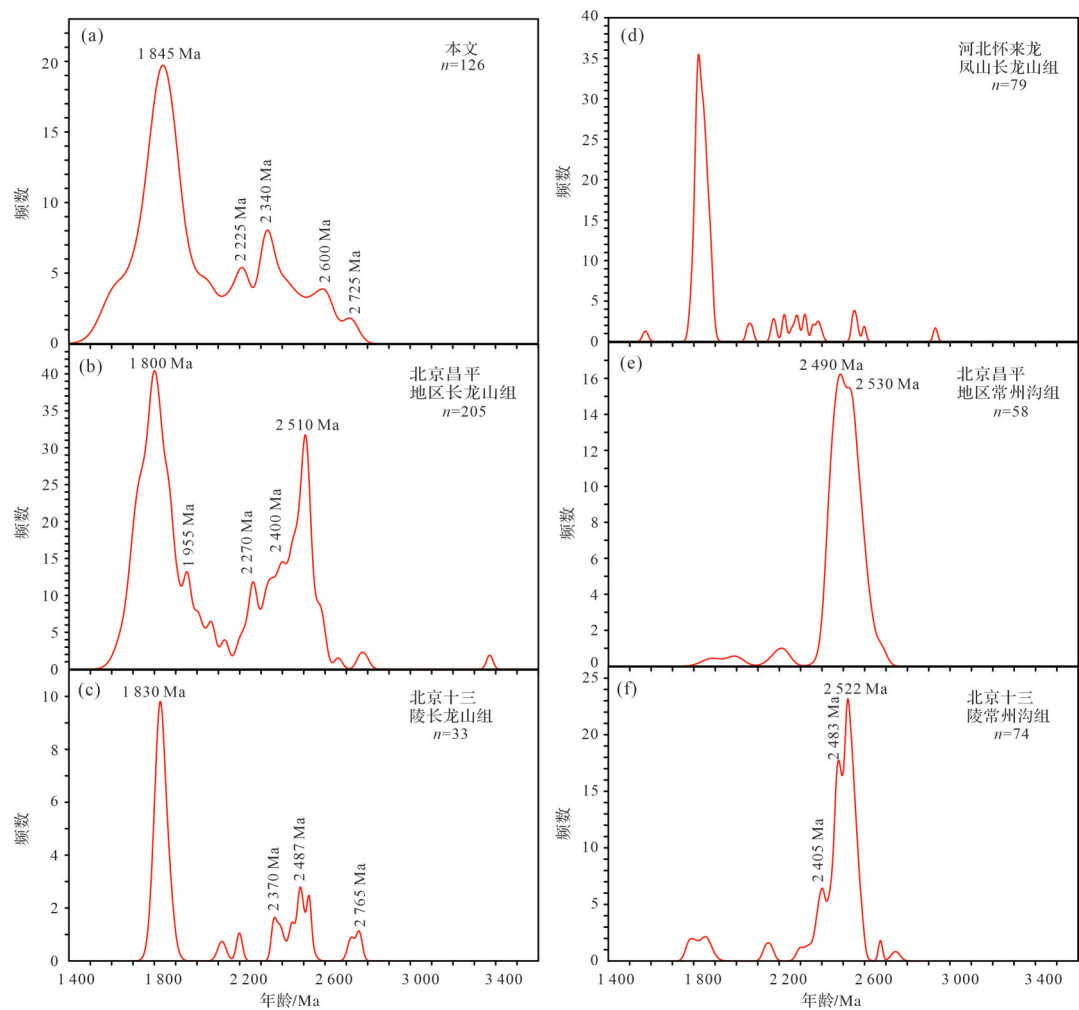


图6 渤海辽东地区砂岩样品和其他可对比地层的锆石年龄分布图
(a)此次研究;(b)北京昌平地区长龙山组^[28]; (c)北京十三陵地区长龙山组^[29]; (d)河北怀来龙凤山长龙山组^[30]; (e)北京昌平地区常州沟组^[28]; (f)北京十三陵地区常州沟组^[29]

Fig.6 Zircon age distribution of sandstone samples and other comparable strata in the Liaodong area of the Bohai Sea
(a) this study; (b) Changlongshan Formation, Changping area, Beijing^[28]; (c) Changlongshan Formation, Shisanling area, Beijing^[29]; (d) Changlongshan Formation, Huailai county, Hebei^[30]; (e) Changzhougou Formation, Changping area, Beijing^[28]; and (f) Changzhougou Formation, Shisanling area, Beijing^[29]

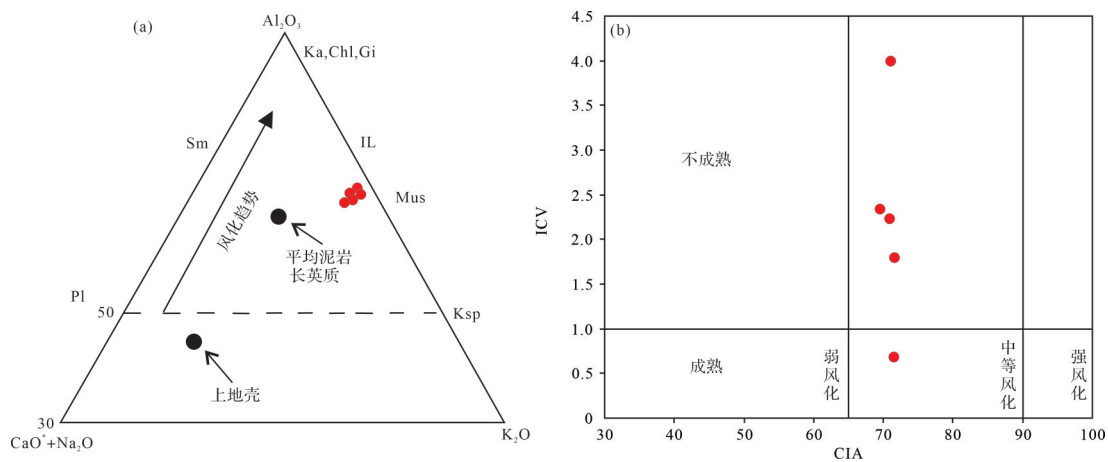


图7 (a) A-CN-K 图解 (据文献[40-41]); (b) ICV-CIA 图解 (据文献[4])
Fig.7 (a) A-CN-K diagram (after references [40-41]); (b) ICV-CIA diagram (after reference [4])

于1,表示主要来源于长英质岩石。在F1-F2判别图中,石英砂岩样品均落在P4区,即古老沉积体系或克拉通/再旋回造山带的长英质沉积岩物源区^[47](图8b)。石英砂岩样品中Zr/Sc和Th/Sc的值具有一定的正相关性($R^2=0.78$),在Zr/Sc和Th/Sc图解中可以看出其投点主要分布在上地壳(长英质岩石)附近,说明样品很可能来自上地壳长英质源^[19](图8c)。

长龙山组石英砂岩碎屑锆石中的Hf同位素数据显示,物源区古元古代(~1.80 Ga)陆壳再循环的岩石显著增多^[28];第五春荣等^[48]对秦皇岛柳江地区长龙山组的碎屑锆石开展了Hf同位素的研究和分析,结果表明该源区物质主要来自古老地壳物质再循环。综上,渤海辽东湾地区新元古界青白口系长龙山组石英砂岩物源来自上地壳长英质岩石,与碎屑锆石研究讨论的物源基本吻合。

4.2 碎屑锆石对华北克拉通前寒武纪地质事件的指示

华北克拉通是全球最古老的陆块之一,它记录了许多前寒武纪全球重大地质事件。例如华北克拉通的陆核形成、陆壳发生过的生长、微陆块拼合与克拉通化等^[49-50],而碎屑锆石U-Pb年龄恰好记录了岩浆形成过程的时间,是认识古老地球形成的重要手段^[51]。

1) ~2.7 Ga和~2.5 Ga的碎屑锆石代表了华北克拉通陆壳生长事件及构造热事件

华北克拉通曾发生过数次陆壳生长事件,前人通过全岩Nd同位素亏损地幔模式年龄和碎屑锆石Hf模式年龄研究分析,认为华北克拉通陆壳生长事件发生在~2.7 Ga和~2.5 Ga^[52-53]。肖玲玲等^[54]对华北克拉通左权地区变质杂岩进行了地球化学和年代学研究,也印证了华北克拉通在~2.7 Ga和~2.5 Ga存在两期构造热事件,华北克拉通也正是经历这两期陆壳生长后才完成了初始克拉通化^[55-56]。王翔等^[57]报道

了华北克拉通霍邱岩群及赋存在其中的BIF铁矿主要形成于~2.7 Ga,同时华北克拉通还存在大量形成于~2.5 Ga的BIF铁矿,说明华北克拉通在~2.7 Ga和~2.5 Ga两个时期均发生了构造热事件。本次石英砂岩样品的锆石年龄图中存在~2.7 Ga和~2.5 Ga的次要峰值,年龄分布在~2.7~2.5 Ga的碎屑锆石约占碎屑锆石总数的11%,这些太古代碎屑锆石的年龄峰值年龄与古太古代中期—新太古代末期陆壳生长事件时间吻合,可能就是~2.7 Ga和~2.5 Ga陆壳生长及构造热事件的记录。

2) 2.20~1.85 Ga的碎屑锆石代表了哥伦比亚超大陆聚合事件

在2.1~1.8 Ga时全球范围内发生了大规模的造山事件,由来自世界各地的多个克拉通拼合形成了哥伦比亚超大陆,这些古老的克拉通中就包含了华北克拉通^[9,58-59]。华北克拉通在形成同一结晶基底之前,东部陆块与西部陆块之间被古大洋所分隔,随着古大洋壳向东部陆块西缘俯冲,并伴随着岩浆活动,在1.88~1.82 Ga时古大洋全部俯冲消失,东部陆块和西部陆块发生碰撞完成克拉通化^[60-61]。肖玲玲等^[62]对吕梁界河口群含榴夕线黑云斜长片麻岩进行研究,其记录了1 928~1 920 Ma和1 882~1 855 Ma两组变质年龄,并认为吕梁地区变质杂岩的区域变质事件与古元古代晚期华北克拉通东、陆块碰撞有关。此外,郭敏洁等^[63]报道了云中山石榴斜长角闪岩的变质锆石U-Pb年龄介于1 928~1 806 Ma;郭敬辉等^[36]在河北宣化地区对角闪岩测年的结果为~1 856 Ma;Guo *et al.*^[37]在河北宣化地区发现了年龄为~1 872 Ma的麻粒岩等,这些研究均为古元古代中期华北克拉通的碰撞造山事件提供了有力的证据。辽东湾地区钻井内的石英砂岩碎屑锆石年龄分布最显著的主要峰值为~1.85 Ga,其分布在2.10~1.85 Ga的碎屑锆石占总

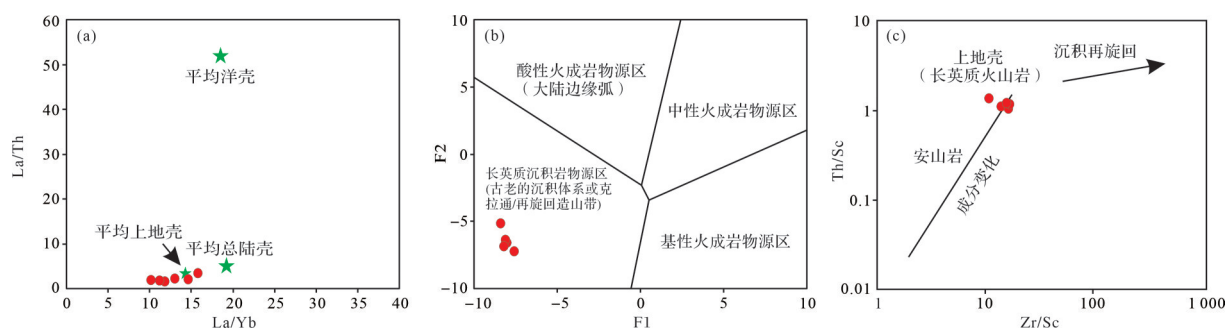


图8 (a) La/Yb-La/Th图解(据文献[45]); (b) F1-F2判别图(据文献[47]); (c) Zr/Sc-Th/Sc图解(据文献[19])

Fig.8 (a) La/Yb-La/Th diagram (after reference [45]); (b) F1-F2 diagram (after reference [47]);

and (c) Zr/Sc-Th/Sc diagram (after reference [19])

数的35%左右,这些碎屑锆石所响应的正是东部陆块和西部陆块拼合形成同一结晶基底事件。

3) 1.8~1.6 Ga的碎屑锆石代表了哥伦比亚超大陆裂解事件

相振群等^[64]认为1.80~1.62 Ga的岩浆事件群是华北克拉通在古元古代晚期持续裂解的具体体现,它们代表了哥伦比亚超大陆早期裂解。康健丽等^[65]在内蒙古固阳地区白云常合山得到的A型花岗岩的年龄为~1 720 Ma;孙立新等^[66]对内蒙狼山北部古元古代变质花岗岩进行定年测试的结果为1 711~1 644 Ma,这些酸性侵入岩的锆石年龄都指示着哥伦比亚超大陆裂解事件^[58,67-68]。另外,杨泽宇等^[69]报道了华北克拉通密云基性侵入岩结晶年龄为~1 673 Ma,其形成时代与全球其他克拉通的基性岩墙群时代耦合,这些在古元古代燕辽裂陷槽拉张伸展环境形成的基性岩墙群进一步印证了哥伦比亚超大陆裂解的时期。本次碎屑锆石年龄分布在1.8~1.6 Ga的碎屑锆石约占碎屑锆石总数的27%,这些碎屑锆石的年龄很可能记录的是哥伦比亚超大陆早期裂解。

5 结论

(1) 渤海辽东湾海域新元古代青白口系长龙山组石英砂岩碎屑锆石年龄分布于2 744~1 581 Ma,其中,主要年龄峰值为~1 855 Ma,次要年龄峰值为~2 725 Ma、~2 585 Ma、~2 335 Ma和~2 225 Ma,碎屑锆石年代学特征反应该套石英砂岩属于新元古代青白口系长龙山组。

(2) 渤海辽东湾地区石英砂岩样品地球化学特征显示其具有较高的SiO₂含量,Th/U、La/Sc、Th/Sc等比值与上地壳相似,La/Yb-La/Th图解和Zr/Sc-Th/Sc图解中石英砂岩样品点均落在上地壳附近。Cr/Zr比值、F1-F2判别图和Zr/Sc-Th/Sc图解指示物源主要来自上地壳长英质岩石。

(3) 碎屑锆石的各个年龄峰值分别记录了华北克拉通太古代至古元古代的数次地质事件:~2.7 Ga对应了华北克拉通的一次陆壳生长事件,~2.5 Ga与华北克拉通发生过剧烈的岩浆活动时间相吻合,主要年龄峰值(~1.85 Ga)记录了华北克拉通东、西两大陆块的碰撞拼合事件,1.8~1.6 Ga对应的岩浆事件可能反应了哥伦比亚超大陆的裂解。

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提供的宝贵意见也使得文章质量较大提高,在此一并感谢。本文所用的石英砂岩碎屑锆石U-Pb年代学和全岩地球化学数据,可以通过国家冰川冻土沙漠科学数据中心获取<http://www.ncdc.ac.cn/portal/magazine/detail?id=ed14bd8b-fb13-4487-93f5-216e5f0d0d86>。

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Characteristics by Provenance of Quartz Sandstone from the Neoproterozoic Changlongshan Formation in the Offshore Liaodong Bay and Its Geological Significance

ZHAO ZiLin¹, ZHOU XueWei¹, LI KuiZhou², GUO Tao³, PENG JingSong³, HOU MingCai^{1,2}

1. Institute of Sedimentary Geology, Chengdu University of Technology & Key Laboratory of Deep Time Geological Environment Reconstruction and Application, Ministry of Natural Resources, Chengdu 610059, China

2. State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China

3. Tianjin Branch of CNOOC China Limited, Tianjin 300452, China

Abstract: [Objective] The quartz sandstone of the Changlongshan Formation in the Qingbaikou system from the Neoproterozoic was encountered during drilling in the southwestern Liaodong Bay, Bohai Sea. The in-depth study of its provenance characteristics is of great significance to the anatomy of major geological events from the Archean to Proterozoic in the North China Craton. [Methods] Five quartz sandstone samples collected from around 2 482 meters in well BD4-1a were analyzed for whole-rock geochemistry and detrital zircon U-Pb geochronology. [Results] The quartz sandstones had high SiO₂ content (88.53%-93.06%), the chemical index of alteration (CIA) value was 69.5~71.6, the index of compositional variability (ICV) value was 0.69-3.99, and the samples displayed high compositional maturity, structural maturity, and moderate weathering. The Th/U ratio ranged from 3.46-4.92, the Cr/Zr ratio of 0.17~0.35. The sum of the rare earth elements (Σ REE) is $(8.26-24.12) \times 10^{-6}$, the low/heavy rare earth element ratio (LREE/HREE) was 6.28~10.21, and the δ Eu was 0.77-1.04, which shows a weak negative anomaly. The U-Pb ages of detrital zircons ranged from 2 744-1 581 Ma; the main age peak was ~1 845 Ma, and the subordinate age peaks were ~2 225, ~2 340, ~2 600, ~2 725 Ma, respectively. [Conclusions] Whole-rock geochemistry indicates that the provenance mainly comes from felsic rocks of the upper crust. The 2.7-2.5 Ga detrital zircons record the growth and tectonothermal events of the continental crust in the North China Craton. The 2.2-1.8 Ga detrital zircons correspond to the crystalline basement formation during the amalgamation of the eastern and western blocks of the North China Craton, recording the geological events of the Columbia supercontinent's assembly. The 1.8-1.6 Ga detrital zircon ages likely record the breakup of the Columbia supercontinent.

Key words: Bohai Sea; detrital zircons; geochemistry; provenance; Columbia supercontinent