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哈尔滨三截地砂砾石堆积地层属性特征 ——对地层区域划分和构造的指示

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摘要 【目的】黑龙江宾县居仁镇的三截地砂砾石曾被视为罗家窝棚组,但其地层属性和沉积环境研究较为薄弱,这极大限制了对该地层所记录的区域地表过程的理解。【方法】通过沉积学、矿物学、元素地球化学和碎屑锆石 U-Pb 年代学等研究方法进行分析讨论。【结果】三截地剖面砂砾石风化程度较低、分选中等、磨圆度较好、无明显定向排列;砾石岩性以花岗质岩石(46.31%)和石英质岩石(28.19%)为主,正长岩(0.20%)、凝灰岩(0.01%)和片岩(0.01%)次之;重矿物组成以楣石(65.18%)和绿帘石(11.87%)为主,其他重矿物含量较少;元素地球化学揭示沉积物具有弱到中等的化学风化程度、大部分沉积物经历了初次循环,其母岩类型为长英质。沉积物元素地球化学的迁移与富集、古气候判别图解和沉积相揭示了区域沉积物为干旱的氧化环境下的曲流河相环境。碎屑锆石 U-Pb 年龄分布范围较窄(134.2~220.3 Ma,年龄峰值在~168 Ma),表明了张广才岭的碎屑贡献,并指示了佳木斯地块和松嫩地块间碰撞—拼合和东侧大洋板块持续俯冲作用。与罗家窝棚组进行对比,三截地剖面沉积环境、地貌单元和构造背景等方面存在差异。推测三截地剖面形成时间比罗家窝棚组晚,大致与白土山组时间相当。【结论】对哈尔滨第四纪地层的划分和区域地表过程的重建提供了新的证据。

关键词 三截地剖面;地球化学;锆石 U-Pb 测年;物源;沉积环境;地层划分

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0 引言

沉积物的沉积是一种重要的地表过程,解译沉积过程、沉积记录的属性是地球表层系统运行的依据(Zheng *et al.*, 2020)。碎屑沉积物是记录过去地质过程的重要信息载体,其元素地球化学特征、沉积学特征和重矿物组成等是判断沉积物古风化作用(Muhs, 2004)、母岩性质(Weltje and von Eynatten, 2004)、构建源区地质构造背景(Andersen *et al.*, 2022)的重要依据;碎屑锆石年龄可以指示岩浆岩地层的沉积年龄,揭示沉积构造环境(Armstrong-Altrin, 2020;冷宇坤等, 2023)。因此,沉积学、矿物

学、元素地球化学和碎屑锆石年龄等手段是重建沉积环境和揭示构造背景的重要方法(徐杰和姜在兴, 2019)。

中国东北哈尔滨地区是典型的第四系发育地区,学者们开展了大量的第四纪地层研究(刘淑秋等, 1985),哈尔滨第四系更新统包括:罗家窝棚组、关家窝棚组、白土山组、荒山组、哈尔滨组和顾家屯组,其中对上更新统和中更新统研究较为完善(吴金城等, 1984;裘善文等, 1988),但对下更新统缺乏研究,尤其缺乏对第四纪最底层单元—罗家窝棚组的研究,因此对罗家窝棚组的研究有助于松嫩平原第四纪地层的划分。由于在20世纪90年代仅限于对

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人类考古、沉积学特征和孢粉的研究而没有进行有关地球化学、矿物学和锆石 U-Pb 年代学的研究,三截地剖面被归纳为罗家窝棚组的砂砾石堆积剖面。早前认为罗家窝棚组是早更新世早期的冰碛物堆积(叶启晓等,1984),但近期研究表明为炎热气候条件下的洪积物堆积(魏春艳等,2022)。为此,厘清三截地剖面砂砾石堆积的沉积环境,对认识区域地表过程具有重要意义。

为了获得三截地剖面所隐含的地表过程信息,对剖面进行沉积学、元素地球化学、重矿物和锆石 U-Pb 年龄分析,讨论该剖面的母岩性质、沉积环境和构造背景,最后与罗家窝棚组进行对比。此项研究对区域构造演化、重建古地理环境,以及哈尔滨第四纪地层的划分等提供了重要依据。

1 研究区概况

哈尔滨(44°04'~46°40' N,125°42'~130°10' E)位于松嫩地块东南部,属于松辽沉降带东南隆起区(王恩宝,2012)。所发育的活动断裂均为隐伏于前第四系以下的基底断裂,区域构造线方向以东北向和北西向为主。罗家窝棚组断续分布在泥砾堆积沿山前平原与滨东丘陵带,地貌上呈现出崩状、条带状和短垄状的特点(叶启晓,1991)。

哈尔滨三截地剖面在宾县居仁镇边缘北侧 2 km 处,南、西与宾西镇相接,北与满井镇接壤,东与宾州镇毗邻。构造上属于杏山—宾县凹陷区,位于依兰—伊通断裂带附近(图 1c)。地貌上处于山间平原和滨东丘陵的过渡区域(图 1d)。

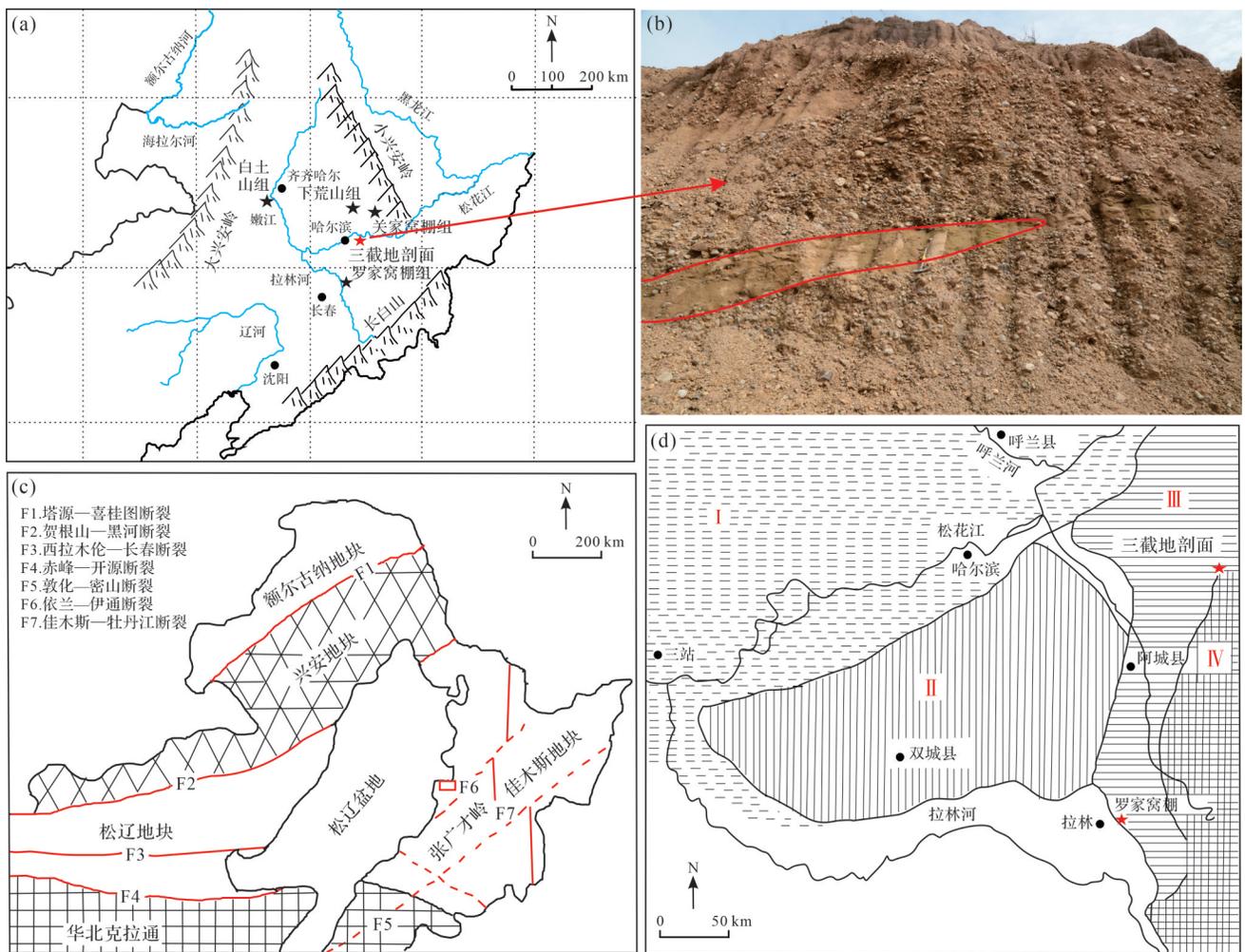


图 1 研究区位置及剖面示意图

(a)研究区位置;(b)三截地剖面照片;(c)区域地质简图(刘军等,2013);(d)地貌单元;I.河谷平原;II.河间平原;III.山间平原;IV.滨东丘陵

Fig.1 Location and profile diagram of the study area

(a) location of the study area; (b) Sanjiedi profile photographs; (c) regional geological map (Liu et al., 2013); (d) geomorphic unit; I. valley plain; II. interfluvial plain; III. intermontane plain; IV. eastern coastal hills

2 研究方法

本文以居仁镇三截地剖面为研究对象,对剖面砾石和细颗粒沉积物进行沉积学、重矿物、地球化学和锆石 U-Pb 测年研究。其中 6 个样品(泥质—粉砂质样品)用于地球化学分析,3 个样品(极细砂—细砂样品)用于重矿物分析,1 个样品(透镜体碎屑物)进行锆石 U-Pb 测年分析。在剖面中选择两个砾石统计点,共计 235 个砾石进行砾径、方位、ab 面产状、砾石的磨圆度和风化程度等统计记录。

重矿物的分选和鉴定工作在河北廊坊诚信地质公司进行,具体实验流程如下:将重矿物样品筛选出 63~250 μm 的组分,经过称重和淘洗之后,利用密度为 2.89 g/cm^3 的三溴甲烷分离出重矿物后用酒精冲洗,冲洗干净后晾干称重。将样品置于光学显微镜下进行实验。每个样品至少取 600 粒重矿物鉴定样品颗粒。

地球化学分析利用研磨分样筛后小于 63 μm 组分的粉末。通过压片法且误差小于 3% 的方法使用荷兰帕纳科 XRF 光谱仪测量常量元素。使用电感耦合等离子体质谱仪(ICP-MS)测试微量、稀土元素数据,检测的数据的相对误差均小于 2%。

碎屑锆石 U-Pb 测年实验在河北廊坊诚谱检测技术有限公司利用 NewWave, NWR193 和 Analytik Jena AG PQMS030 仪器(德国)进行测量,剥蚀频率为 8 Hz,激光光斑直径为 30 μm 。详细的流程和定年主标样见文献(Griffin *et al.*, 2004)。年龄谐和图的制作

采用软件 Isoplot4.15 完成。

3 结果

3.1 沉积学特征

三截地剖面由黄褐色粉质黏土及砂、砂砾石组成,砾石层主要表现出斜层理特征(图 2a),具有典型的河漫滩二元结构(图 2c)。

砾石砾径集中在 20~200 mm,最大为 500 mm(图 3a);砂砾石分选中等,没有明显的定向排列。砾石岩性主要以花岗质岩石(46.31%)、石英质岩石(28.19%)和砂岩(16.11%)为主,正长岩(0.20%)、凝灰岩(0.01%)和片岩(0.01%)次之(图 3b)。砾石磨圆度中次圆(75.32%)占主要优势,其次为次棱角(14.47%)、圆(9.36%)和极圆(0.08%)(图 3c)。砾石化学风化特征以弱风化(48.94%)和中等风化(40.43%)为主,其次为强风化(10.21%)和无风化(0.04%)(图 3d)。

3.2 重矿物组成

哈尔滨三截地剖面的重矿物有锆石、钛铁矿、赤褐铁矿、磁铁矿、磁黄铁矿、榍石、白钛石、磷灰石、绿帘石共 9 种,其中磁黄铁矿仅在一个样品中出现(表 1)。重矿物以榍石(65.18%)和绿帘石(11.87%)为主,其次为锆石(2.28%)、磷灰石(5.60%)、钛铁矿(2.77%)、赤褐铁矿(3.41%)、磁铁矿(5.15%),白钛石(0.54%)和磁黄铁矿(0.10%)不足 1%,其他重矿物占 3.11%。

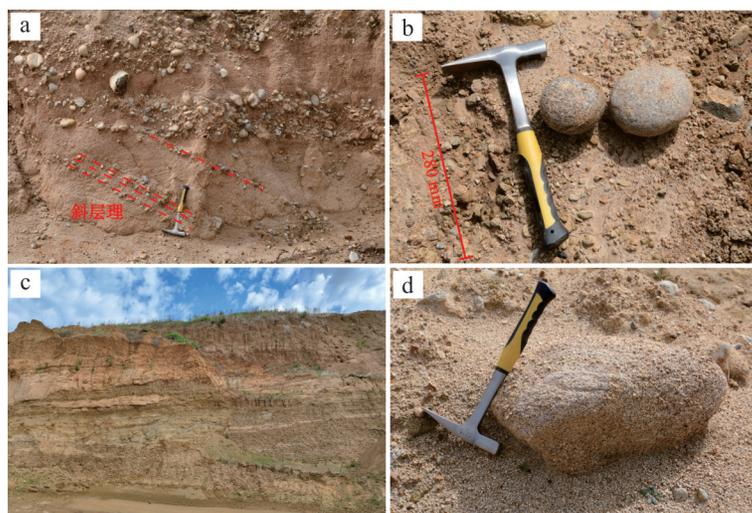


图 2 三截地剖面沉积学特征

(a) 砾石层的层理及斜层理; (b) 磨圆度极好的花岗岩砾石; (c) 河漫滩典型二元结构; (d) 强风化的花岗岩砾石

Fig.2 Sedimentological characteristics of the Sanjiedi profile

(a) bedding and oblique bedding of gravel layers; (b) highly rounded granite gravel; (c) typical binary structure of floodplain; (d) strongly weathered granite gravel

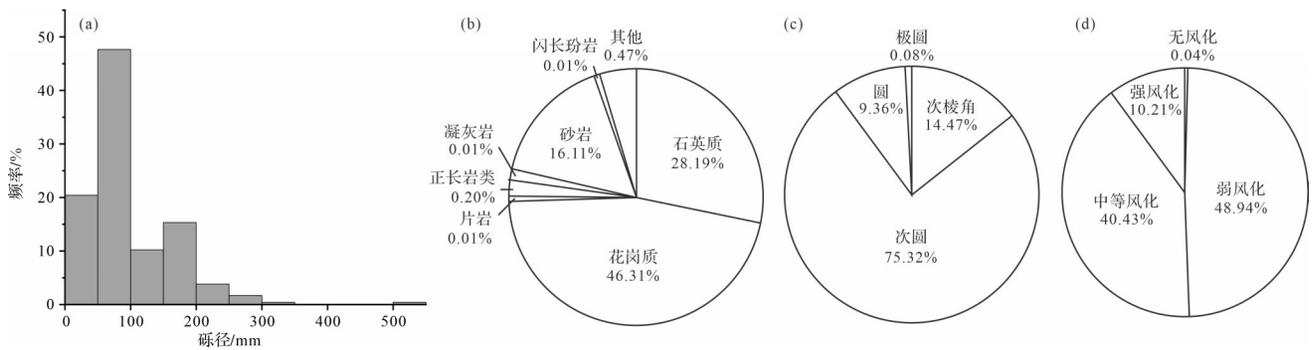


图3 三截地剖面砾石特征

(a)砾石砾径频率分布直方图;(b)砾石岩性;(c)砾石磨圆度;(d)砾石风化程度

Fig.3 Properties of gravel in Sanjiedi profile

(a) frequency distribution of gravel diameter; (b) lithology; (c) roundness; (d) degree of weathering

表1 三截地剖面重矿物组成(%)

Table 1 Heavy mineral composition (%) of stratigraphic section, Sanjiedi profile

样品名称	锆石	钛铁矿	赤褐铁矿	磁铁矿	磁黄铁矿	榍石	白钛石	磷灰石	绿帘石	其他
SJD-2	2.52	4.35	1.26	0.71	0	67.02	0.97	6.29	13.08	3.80
SJD-3	2.32	1.69	8.14	0.14	0	68.61	0.33	4.35	9.99	4.43
SJD-4	2.35	2.71	1.37	15.41	0.31	70.20	0.39	7.06	14.41	1.58

3.3 常量元素

哈尔滨三截地剖面的常量元素丰度为: SiO₂ (60.21%~69.09%, 平均值为63.43%), Al₂O₃ (20.18%~15.65%, 平均值为18.26%), Fe₂O₃ (8.84%~2.95%, 平均值为6.73%), K₂O (4.85%~2.52%, 平均值为3.35%) (n=6)。而其他常量元素 MgO、CaO、Na₂O、MnO、TiO₂、P₂O₅ 含量较低, 平均值分别为1.48%、2.27%、2.19%、0.06%、1.09%、0.31%。与UCC(大陆上地壳)相比, SiO₂、K₂O 含量接近UCC, 其他元素显示出不同程度的富集或亏损。Al₂O₃ 轻微富集, MgO、CaO、Na₂O、MnO、P₂O₅ 表现出不同程度的亏损, Fe₂O₃、TiO₂ 明显富集(图4a)。

3.4 微量元素

三截地剖面微量元素变化复杂。与UCC相比, 过渡元素(TTE: Sc、V、Cr、Co、Ni、Cu、Zn、Ca)中, Sc 含量与UCC较为接近, V、Zn、Ca 表现出不同程度的富集, 而Cr、Co、Cu 出现亏损, Ni 出现明显亏损。高场强元素(HFSE: Y、Zr、Nb、Hf、Ta、Th、U)中, Zr、Ta 表现出不同程度的富集与亏损, Y、Th、U 明显富集, Nb 和 Ta 轻微亏损。大离子亲石元素(LILE: Rb、Sr、Cs、Ba、Pb)中, Pb 含量接近UCC, 在Rb、Sr 和Ba 中出现亏损, Cs 出现不同程度的富集或亏损(图4b)。

3.5 稀土元素

三截地剖面沉积物的稀土总量介于166~244, 平均值为215, 明显高于UCC(146.37)和PAAS(184.77)

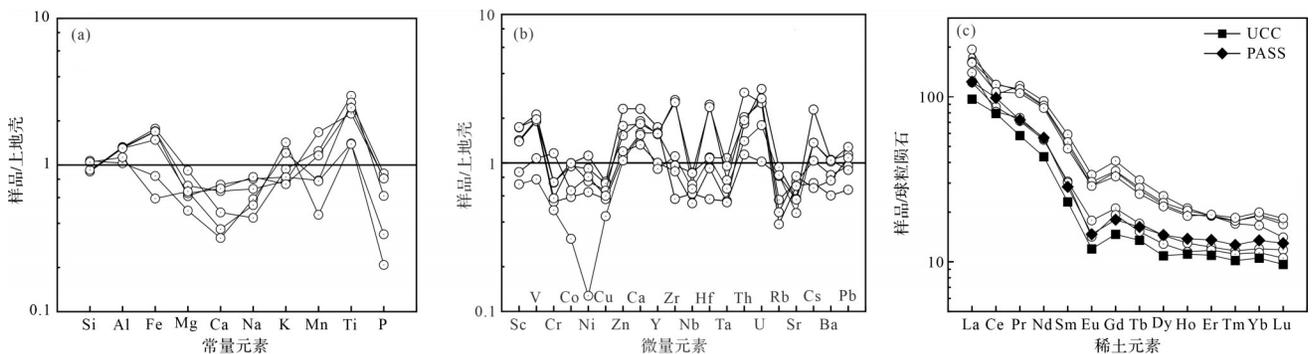


图4 三截地剖面细颗粒组沉积物的元素标准化模式图

(a)常量元素分配模式图;(b)微量元素分配模式图;(c)稀土元素分配模式图

Fig.4 Normalized patterns of elements in fine-grain materials, Sanjiedi profile

(a) constant element allocation pattern diagram; (b) trace element distribution pattern; (c) rare earth element distribution pattern

(Taylor and McClelland, 1985)。沉积物轻稀土元素总量介于157~229,平均值为202;重稀土元素总量介于8~16,平均值为13。 Σ LREE/ Σ HREE 介于7.57~9.77,平均值为8.33。 $(La/Sm)_N$ 值介于3.07~4.64,平均值为3.61,稀土元素配分曲线总体上呈现“左陡右缓”的分布趋势,表现相对富集轻稀土元素、亏损重稀土元素。 $(La/Yb)_N$ 值介于8.08~12.35,平均值为10,表明轻重稀土分异明显,轻稀土富集。 $(Gd/Yb)_N$ 值介于1.70~2.47,平均值为1.89,表明重稀土元素分馏程度明显。 Ce/Ce^* 平均值为0.79, Eu/Eu^* 平均值为0.67,表明三截地剖面存在Ce、Eu负异常(图4c)。

3.6 锆石U-Pb测年

三截地剖面的大部分锆石颗粒具有明显的振荡环带结构,Th/U比值均大于0.1,表现出典型岩浆锆石特征。几乎所有的测点均位于U-Pb谐和线附近,剔除谐和度小于90%的锆石年龄数据,对小于1 000 Ma的年龄采用 $^{206}Pb/^{238}U$ 年龄,绘制了碎屑锆石U-Pb年龄谱。本次一共有120个颗粒数,锆石 $^{206}Pb/^{238}U$ 年龄加权平均为 174.6 ± 9.7 Ma (MSWD=

0.28)。碎屑锆石U-Pb年龄主要分布在134.2~220.3 Ma,年龄峰值在168 Ma左右(图5a)。大兴安岭的锆石年龄主要集中在145~120 Ma(图5b),小兴安岭的锆石年龄谱主要有两个阶段,260~290 Ma和160~171 Ma(图5c),张广才岭的锆石年龄主要集中在175~222 Ma(图5d)。

4 讨论

4.1 化学风化强度

化学风化作用是源—汇沉积体系中的重要环节,其对风尘物源贡献评估、追踪气候演化和了解地质过程等具有重要的指示意义(Maharana *et al.*, 2018; 张曼, 2021)。化学风化过程会优先去除不稳定的阳离子(如 K^+ 、 Na^+ 和 Ca^{2+}),保留稳定的阳离子(Ti^{4+} 和 Al^{3+}),改变碎屑沉积物的化学成分。因此,化学风化作用增强,沉积物中稳定矿物越多,而不稳定矿物越少(张英利等, 2019)。三截地剖面重矿物样品中稳定重矿物(锆石、榍石、磁铁矿、赤褐铁矿)富

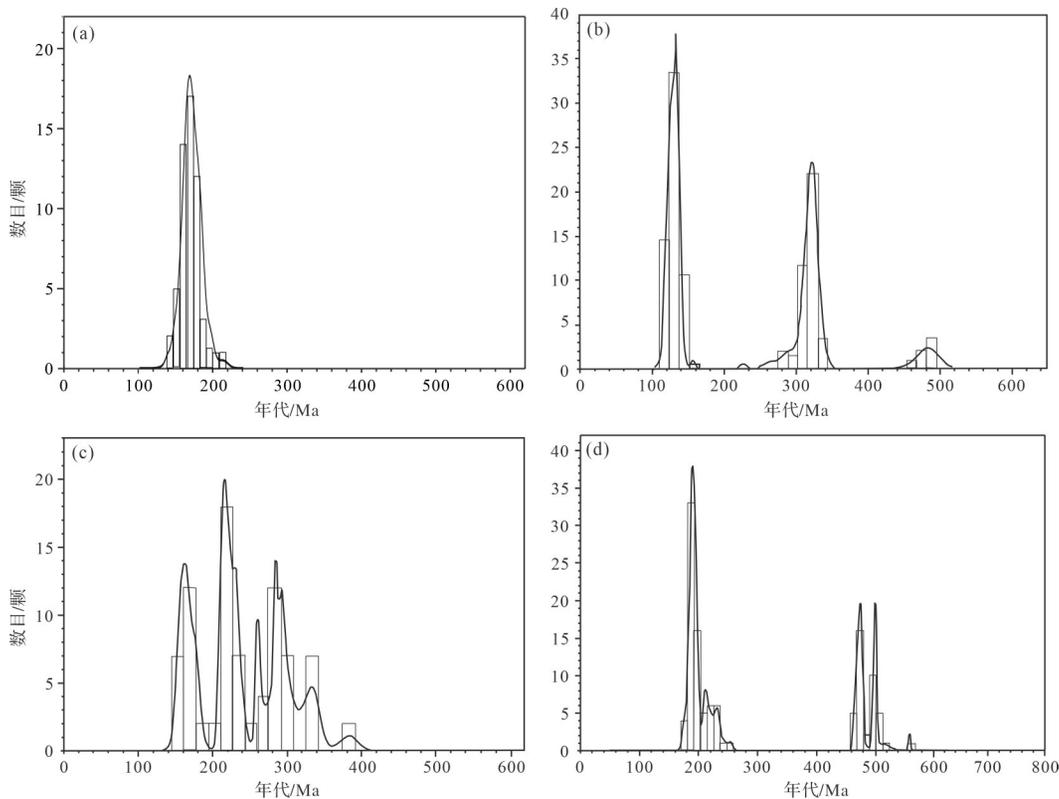


图5 年龄频谱图

(a)三截地剖面锆石碎屑;(b)大兴安岭造山带中南部(鲍庆中等,2007;葛文春等,2007);(c)小兴安岭西北部造山带(孙德有等,2000,2004);(d)张广才岭造山带(刘建峰等,2008;陈雷等,2009)

Fig.5 Age spectrometry

(a) Sanjiedi profile orogenic belt; (b) central and southern Great Xing'an Range orogenic belt (Bao *et al.*, 2007; Ge *et al.*, 2007); (c) northwestern Xiao Hingan Mountains orogenic belt (Sun *et al.*, 2000, 2004); (d) Zhangguangcailing orogenic belt (Liu *et al.*, 2008; Chen *et al.*, 2009)

1.29,因此,三截地剖面样品属于初次循环的沉积物(图7a)。

K_2O/Na_2O 比值也可以用来了解沉积物的分选和再循环(李徐生等,2007)。由于斜长石相对于钾长石更容易发生风化作用,因此随着风化作用的增加, K_2O/Na_2O 也会增加。 K_2O/Na_2O 比值大于1表明化学成熟度较高。 K_2O/Na_2O 比值小于1说明化学成熟度低(Armstrong-Altrin and Machain-Castillo, 2016; 徐小涛和邵龙义, 2018)。三截地剖面的样品比值介于0.78~2.33,平均值为1.44,高于UCC(0.87)而低于PAAS(3.08),表示三截地剖面样品成熟度高,属于初次循环的沉积物。

利用Th/Sc-Zr/Sc图区分沉积物分选和再旋回作用(李俊等,2024)。Th/Sc比值指示火成岩化学分异过程,Zr/Sc是锆石富集的有用指标(McLennan et al., 1993)。若样品沿着岩浆分异趋势线分布说明沉积物属于初次循环;样品沿着再循环趋势线分布说明沉积物受再循环的影响。因此,从三截地剖面样品的分布可以看出沉积物属于初次循环产物(图7b)。

4.3 源岩性质

地球化学数据可以反映源岩性质,尤其稀土元素和微量元素能够较为完整地保存物源区信息,是判断物源母岩类型的有效工具(呼其图等,2024)。通常情况下,稀土元素较高的LREE/HREE值、负Eu异常指示岩石母岩为长英质(董策和周建波,2012)。在三截地剖面中,LREE/HREE值较高且Eu/Eu*平均值为0.68,Eu负异常,表明三截地剖面沉积物源于长英质岩石。岛弧火山岩Th/U值介于2.5~3.0,沉积岩

为4.5,再旋回沉积岩为6(王久懿等,2023)。三截地剖面样品的Tu/U值介于2.23~4.49,平均值为3.29,表明三截地剖面沉积物母岩是火山岩。

La、Th和Hf在成岩过程中较难被分馏,因此能有效地指示母岩性质(马英军和刘丛强,1999)。在La/Th-Hf图解中,三截地剖面样品落在花岗岩和酸性长英质弧岛区周围,反映三截地沉积物主要为偏酸性长英质母岩(图8a)。在Y/Ni-Cr/V图解中,三截地剖面样品落在长英质火山岩和花岗岩周围,围绕着TTG和UCC(图8b)。利用Co/Th-La/Sc图解可以反映某些岩石大类的成因特征。三截地剖面样品Co/Th值介于0.19~0.54,平均值为0.31,La/Sc值介于2.60~5.49,平均值为3.67,样品点落在长英质火山岩和花岗岩之间(图8c)。利用源岩判别函数F1-F2对母岩属性进行判断(Roser and Korsch, 1988)。三截地剖面中四个样品落在中性火成岩物源区,两个样品落在长英质火成岩物源区(图8d)。以上图解表明三截地剖面沉积物具有长英质性质。三截地剖面砾石岩性以花岗质岩石、石英质岩石和石英质砂岩为主,而张广才岭广泛发育该类岩石(张立仕等,2021),推测三截地剖面源岩主要来源于张广才岭。

4.4 沉积环境

从沉积学和元素地球化学的角度可对沉积环境进行分析(李忠等,2004)。此外,还可从形成水动力、砾石磨圆度、砾石砾径等进行判别(王昆山等,2014)。三截地剖面砾石砾径在20~200 mm;磨圆度以次棱角一次圆为主(占89.79%);剖面中含有棕黄色泥质—粉砂质夹层;斜层理特征明显(图

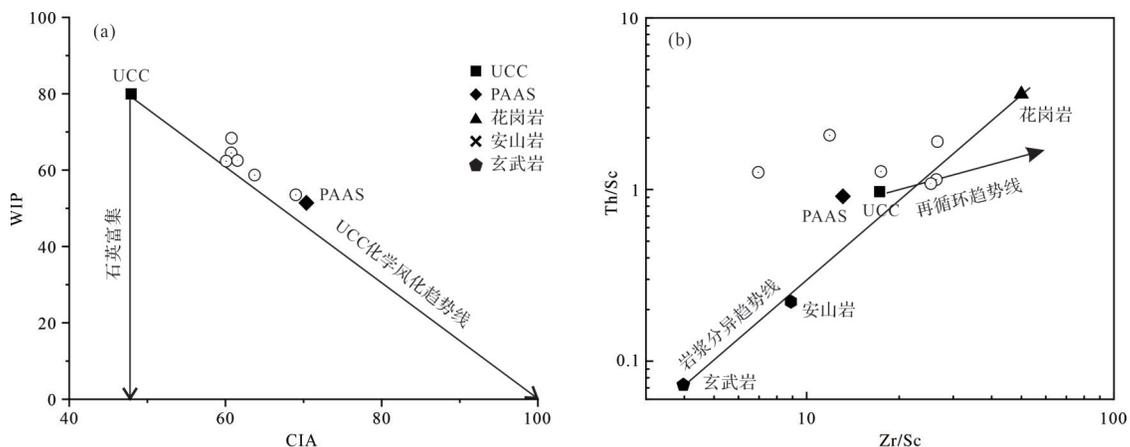


图7 三截地剖面沉积物沉积循环判别图解

(a) CIA-WIP图; (b) Zr/Sc-Th/Sc 二元图解

Fig.7 Illustration of sedimentary cycle discrimination in Sanjiedi profile

(a) CIA-WIP; (b) Zr/Sc-Th/Sc binary diagram

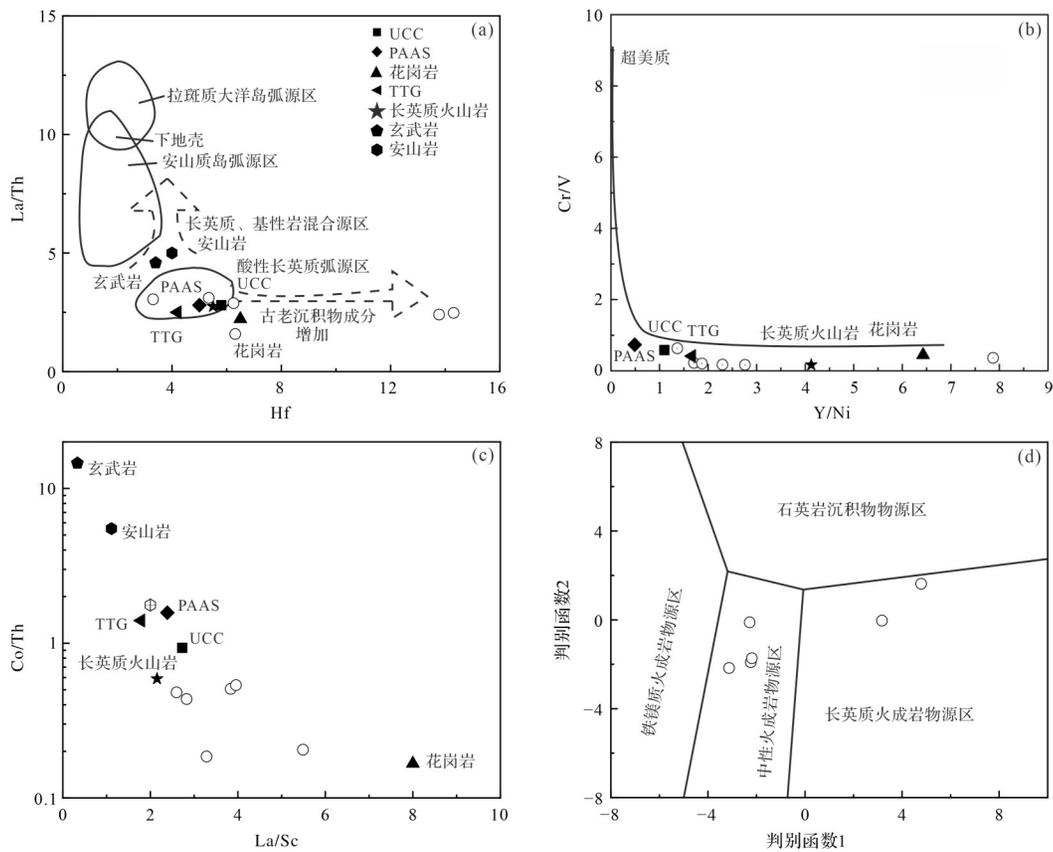


图8 三截地剖面沉积物的母岩性质判别图解 (Floyd and Leveridge, 1987; Gu *et al.*, 2002)

(a) Hf-La/Th 判别图; (b) Y/Ni-Cr/V 判别图; (c) La/Sc-Co/Th 判别图; (d) 源岩判别函数

Fig.8 Graphical discrimination of parent rock properties of sediment in the Sanjiedi profile

(a) Hf-La/Th; (b) Y/Ni-Cr/V; (c) La/Sc-Co/Th; (d) source rock discriminant function

2a); 存在河漫滩典型的二元结构(图2c)。曲流河砾石磨圆度较好,分选中等;发育平行层理、斜层理;一般为泥砂沉积;多发育在河流中下游的河漫滩平原(常西玲等,2023)。因此,推断三截地剖面为曲流河沉积。

Ni/Co 和 V/Cr、U/Th 和 V/(V+Ni) 比值是判断沉积物氧化还原环境的可靠指标(宋立军等,2016),相对而言 Ni/Co 和 V/Cr 比值对缺氧或还原环境判别准确(Jones and Manning, 1994)。当 Ni/Co 大于 5、V/Cr 小于 2 处于富氧环境;Ni/Co 大于 7、V/Cr 大于 4.5 处于缺氧环境(马明等,2016)。在图解中,三截地剖面样品大多落在含氧—还原的过渡区间,指示氧化的沉积环境(图9a)。Ce/Ce* 可以灵敏地反应沉积环境的氧化还原条件(吴子杰等,2024)。Ce/Ce* 大于 1,指示为还原环境;Ce/Ce* 小于 1,指示为氧化环境。三截地沉积物的 Ce/Ce* 的比值介于 0.65~0.88,平均值为 0.79。综上表明三截地剖面的沉积环境为氧化环境。

碎屑岩的化学风化参数(CIA)可以定量地表征

其风化程度进而反映气候条件(Nesbitt and Young, 1982)。其中 CIA=50~65 表示气候干燥;CIA=65~85 表示气候温暖湿润;CIA=85~100 表示气候炎热潮湿(Fedo *et al.*, 1995;张衡等,2019)。三截地剖面沉积物的 CIA 值介于 60~69,平均值为 63,处于干燥的气候环境。再结合 SiO₂-(Al₂O₃+K₂O+Na₂O)图解,图解中沉积物位于干旱区域,表明三截地剖面干旱化的沉积环境(图9b)。Sr/Cu 可作为古气候变化的灵敏度指标。Sr/Cu 比值介于 1.3~5.0 指示温湿气候,比值大于 5.0 指示干热气候(Parrish, 1980;彭治超等,2018)。三截地剖面沉积物 Sr/Cu 比值介于 10.73~17.55,表明其干热的气候条件。

综合沉积学特征和元素地球化学数据,推测三截地剖面属于干旱的氧化条件下的曲流河沉积物。

4.5 构造背景

稀土元素及一些惰性元素在沉积成岩作用中稳定性较好,常用于物源区属性和大地构造背景研究(Bhatia and Crook, 1986;张茜等,2020)。三截地剖面

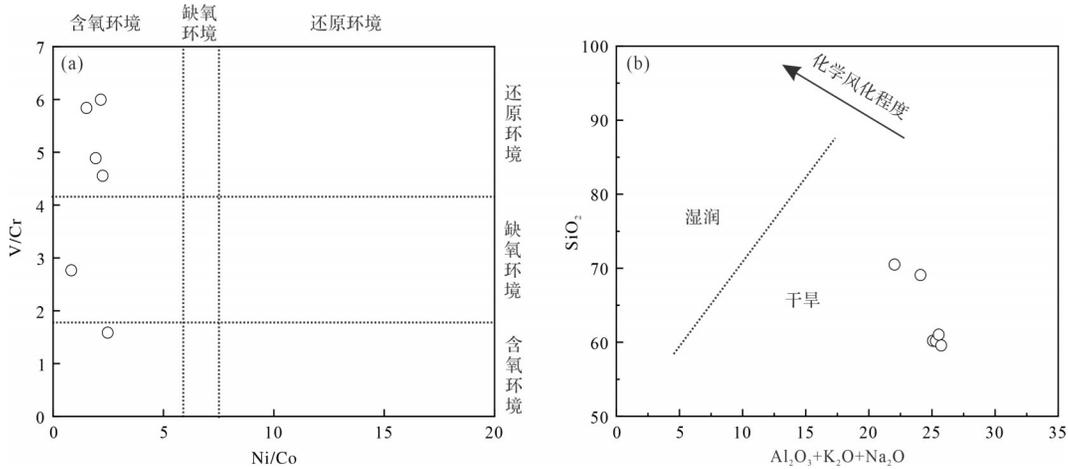


图9 三截地剖面古气候判别图解 (Suttner and Dutta, 1986)

(a) Ni/Co-V/Cr 判别图; (b) 古气候判别图

Fig.9 Illustration of stratigraphic paleoclimate discrimination in Sanjiedi profile (Suttner and Dutta, 1986)

(a) Ni/Co-V/Cr discrimination diagram; (b) paleoclimate discrimination map

沉积物稀土元素各元素比值(表2)(Bhatia, 1985)对比表明,沉积物介于被动陆缘和活动陆缘之间,更接近于被动陆缘。不同构造背景下的沉积岩微量元素 La-Th-Sc、Th-Sc-Zr/10 图解可以有效地识别被动大陆

边缘、活动大陆边缘、大洋岛弧、大陆岛弧等构造背景 (Bhatia and Taylor, 1981; 靳立杰等, 2022)。三截地剖面样品在图解中均落在被动大陆边缘区域,揭示了三截地剖面形成于大陆边缘(图10)。

表2 不同大地构造背景下的REE特征

Table 2 REE properties for different tectonic backgrounds

构造背景	源区类型	La/ $\times 10^{-6}$	Ce/ $\times 10^{-6}$	Σ REE/ $\times 10^{-6}$	La/Yb	La _N /Yb _N	LREE/HREE	Eu/Eu*
被动陆缘	克拉通内	39	85	210	15.9	10.8	8.5	0.56
活动陆缘	基底隆起	37	78	186	12.5	8.5	9.1	0.60
大陆岛弧	切割岩浆弧	27 \pm 4.5	59 \pm 8.2	146 \pm 20	11.0 \pm 3.6	7.5 \pm 2.5	7.7 \pm 1.7	0.79 \pm 0.13
大洋岛弧	未切割岩浆弧	8 \pm 1.7	19 \pm 3.7	58 \pm 10	4.2 \pm 1.3	2.8 \pm 0.9	3.8 \pm 0.9	1.04 \pm 0.11
三截地剖面		49.2	82.9	215	14.8	10	8.3	0.67

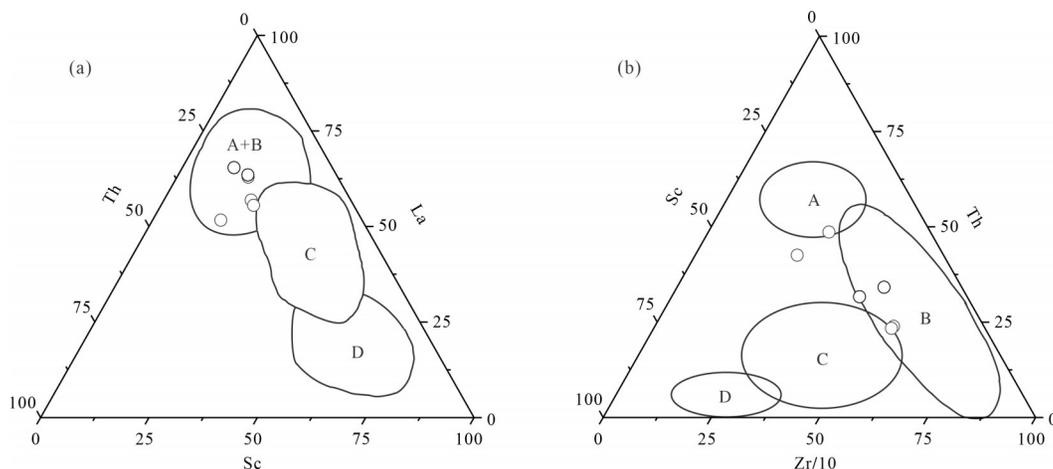


图10 三截地剖面沉积物大地构造背景判别图解

(a) La-Th-Sc 三角判别图解; (b) Th-Sc-Zr/10 三角判别图解; A. 活动大陆边缘; B. 被动大陆边缘; C. 大陆岛弧; D. 大洋岛弧

Fig.10 Discriminant diagrams of tectonic setting of Sanjiedi profile sediments

(a) La-Th-Sc; (b) Th-Sc-Zr/10; A. active continental margin; B. passive continental margin; C. continental island arc; D. oceanic island arc

母岩结晶时代和区域母岩来源可以通过碎屑锆石 U-Pb 年龄体现(李林林,2018)。三截地剖面周围区域有大兴安岭造山带、小兴安岭造山带和张广才岭造山带,为了判断其剖面沉积物的源区,对比分析剖面锆石年龄与三者已有锆石年龄资料。大兴安岭的锆石年龄主要集中在 145~120 Ma(鲍庆中等,2007;葛文春等,2007),小兴安岭的锆石年龄谱主要有两个阶段:260~290 Ma 和 160~171 Ma(孙德有等,2000,2004),张广才岭的锆石年龄主要集中在 175~222 Ma(刘建峰等,2008;陈雷等,2009)。因此,通过锆石 U-Pb 年龄谱可以发现,三截地剖面的碎屑锆石年龄大致与张广才岭和小兴安岭的锆石年龄相似。但是由于 200 Ma 的锆石比例过高使得小兴安岭不符合三截地剖面的源区。因此,说明三截地剖面的主要物源区为张广才岭。

在中侏罗世,张广才岭位于中亚造山带的东段,东侧大洋板块持续俯冲,形成具壳幔混合成因的 I 型花岗岩(任永健,2019;杨浩等,2022)。张广才岭是佳木斯地块和松嫩地块俯冲—碰撞造山带,180~160 Ma 牡丹江洋闭合,佳木斯地块和松嫩地块碰撞—拼合产生了大量的岩浆活动,形成了火山弧花岗岩和碰撞构造环境(张国宾等,2022)。三截地剖面位于张广才岭西侧,其碎屑锆石 U-Pb 年龄主要分布在 134.2~220.3 Ma,年龄峰值在~168 Ma,这为佳木斯地块和松嫩地块间碰撞—拼合和东侧大洋板块持

续俯冲作用提供了新的证据。这表明当时的源区经历了强烈的构造隆升,形成了大陆边缘地质背景。此外,黑龙江杂岩大部分锆石为岩浆锆石,其峰值在早一中侏罗世(185~165 Ma),说明当时经历了快速构造抬升(董玉,2018),这也与三截地剖面锆石年龄峰值(~168 Ma)相对应。

4.6 地层对比与划分

在早期的研究中将三截地剖面归纳为哈尔滨地区第四系下更新统(下限)最老的地层——罗家窝棚组,其地层年龄被确定为约 2.3~2.6 Ma(孙磊,2023)。罗家窝棚组是炎热气候条件下的洪积物堆积,反映的是一套气候地层;在源—汇过程中也反映了一定的构造抬升,指示松嫩平原周围山脉可能在 2.3 Ma 开始隆升(孙磊,2023)。将三截地剖面与罗家窝棚组进行分析对比,发现其在沉积学和地球化学等方面存在显著差异。

首先是沉积环境,罗家窝棚组是炎热气候条件下的冲洪积沉积;三截地剖面是干旱气候条件下的曲流河流沉积。其次从元素地球化学方面,罗家窝棚组的 CIA 值介于 72~95,平均值为 84,化学风化程度强烈;三截地剖面的 CIA 值介于 60~69,平均值为 63,反映弱—中等的化学风化强度,两者在成熟度和再循环方面同样也存在着差异。最后观察基质,罗家窝棚组和三截地剖面的基质性质分别为紫红色黏土(图 11a)和棕黄色黏土(图 11b)。从沉积环境和沉

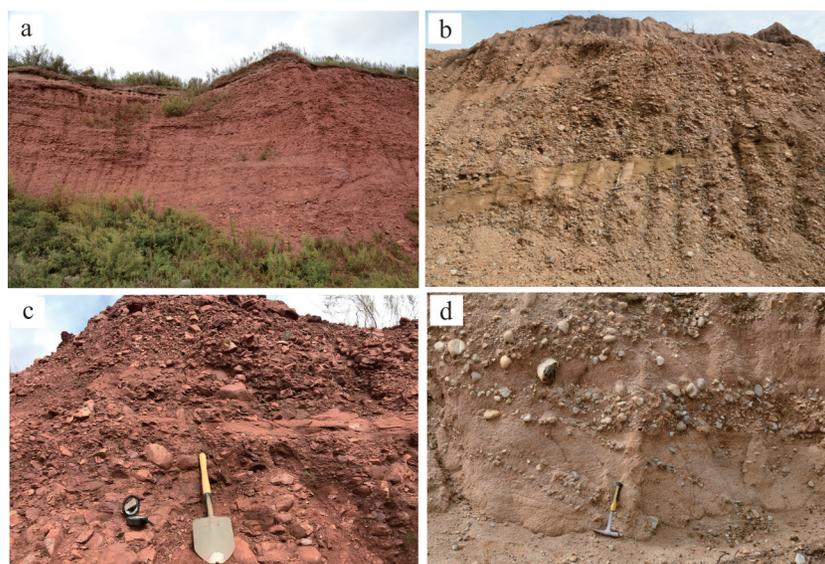


图 11 罗家窝棚组和三截地剖面沉积学特征对比

(a) 罗家窝棚组剖面; (b) 三截地剖面; (c) 罗家窝棚组泥质透镜体; (d) 三截地剖面的砾石层理

Fig.11 Comparison of sediment properties, Luojiawopeng Formation and Sanjiedi profile

(a) Luojiawopeng Formation profile; (b) three section ground profile; (c) Luojiawopeng muddy lens; (d) gravel bedding in Sanjiedi profile

积物颜色可以推断出三截地剖面的形成年龄晚于罗家窝棚组。

此外,从沉积学特征来看,三截地剖面是一套棕黄色弱固结砂砾石堆积(图1b);罗家窝棚组的磨圆度(次圆与圆占21%)明显低于三截地剖面的磨圆度(次圆与圆占85%);罗家窝棚组的砾石岩性以砂岩—粉砂岩(44%)为主,流纹岩和玄武岩(1%)最少,三截地剖面的砾石岩性以花岗质(46%)+石英质(28%)为主。从地层结构来看,罗家窝棚组存在透镜体细颗粒物,而三截地剖面中存在细粒含泥质夹层,并且夹层的层理特征明显(图2a)。其次从重矿物角度对比来看,罗家窝棚组以赤铁矿/褐铁矿(87.5%)为主,不稳定矿物几乎不见,三截地剖面以楣石(65.1%)占绝对优势,不稳定矿物(凝灰石、绿帘石)存在其中。构造地貌单元方面,罗家窝棚组处于山间平原区域;三截地剖面处于山间平原和滨东丘陵的过渡区域。在物源区地质背景方面,罗家窝棚组解释指示了佳木斯地块和松嫩—张广才岭地块俯冲碰撞过程以及牡丹江洋的闭合(孙磊,2023);三截地剖面记录了佳木斯地块和松嫩地块间碰撞—拼合和东侧大洋板块俯冲作用。

与罗家窝棚组进行分析对比说明三截地剖面沉积环境、地貌单元和构造背景等方面存在差异。因此,早期把三截地剖面归纳进罗家窝棚组是不正确的。经过前人资料研究表明比罗家窝棚组更晚的地层:关家窝棚组、白土山和下荒山组。从沉积类型来看,关家窝棚组属于更新世初气候回暖转湿条件下发育的湖沼相堆积物,其形成年龄在1.8~2.1 Ma(王恩宝,2012);白土山组属于河流改造作用下发育的冲—洪积物,其形成年龄在0.8~1.0 Ma(缪振棣等,1984);下荒山组为冷干气候条件下发育的河湖相—湖滨相沉积,其形成年龄在0.781~0.900 Ma(孙建中,2005)。因此,根据沉积环境和沉积类型推测三截地剖面可能是白土山组在哈尔滨西部的同期异相,形成年代较为接近。但是仅仅依据沉积环境和沉积类型对三截地剖面进行地层划分无法确定其剖面准确形成时间,还需要更加精确的测年方法加以确定。

5 结论

(1) 三截地剖面沉积物以棕黄色砂砾石为主,夹杂泥质夹层,局部可见斜层理。砾石分选中等,无明显定向排列,以弱风化(48.94%)和中等风化

(40.43%)为主,砾石磨圆度以次圆(75.32%)为主,砾石岩性以花岗质岩石(46.31%)、石英质岩石(28.19%)为主。

(2) 结合化学风化指标(CIA和PIA)、A-CN-K和A-CN-K-FM三元图解、Fe/Mg比值表明三截地剖面沉积物经历了弱—中等化学风化。综合ICV、WIP、CIA/WIP和 K_2O/Na_2O 比值和Th/Sc-Zr/Sc图解,表明三截地剖面沉积物为初次循环产物。

(3) 综合稀土元素、微量元素比值图解,砾石岩性组成和矿物学分析,三截地剖面沉积物来源于中—酸性岩浆母岩。古气候分析表明三截地剖面经历了干旱的沉积环境,再结合沉积学判断三截地剖面沉积物是干旱的氧化环境下的曲流河流沉积物。

(4) La-Th-Sc、Th-Sc-Zr/10图解判断三截地剖面处于大陆边缘的构造背景。对比锆石年龄谱认为三截地剖面的物源区来源于张广才岭。碎屑锆石年龄(~168 Ma)为佳木斯地块和松嫩地块间碰撞—拼合和东侧大洋板块持续俯冲作用提供了新的证据。

(5) 三截地剖面与罗家窝棚组在沉积物颜色、沉积环境、地貌单元和构造背景等方面存在差异。三截地剖面的形成时间可能晚于罗家窝棚组,推测三截地剖面是白土山组在哈尔滨西部的同期异相,形成年代较为接近。

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参考文献(References)

- 鲍庆中,张长捷,吴之理,等. 2007. 内蒙古白音高勒地区石炭纪石英闪长岩 SHRIMP 锆石 U-Pb 年代学及其意义[J]. 吉林大学学报(地球科学版), 37(1): 15-23. [Bao Qingzhong, Zhang Changjie, Wu Zhili, et al. 2007. SHRIMP U-Pb zircon geochronology of a Carboniferous quartz-diorite in Baiyingaole area, Inner Mongolia and its implications[J]. Journal of Jilin University (Earth Science Edition), 37(1): 15-23.]
- 常西玲,郭进京,常璐璐,等. 2023. 西秦岭北缘渐新世砾岩沉积特征

- 及沉积环境:渐新世—中新世盆地构造环境约束[J]. 沉积学报, 41(5): 1495-1511. [Chang Xiling, Guo Jinjing, Chang Lulu, et al. 2023. Characteristics of Oligocene conglomerates and their sedimentary environment in the northern margin of west Qinling: Constraints on the tectonic setting of the Oligocene-Miocene basin[J]. Acta Sedimentologica Sinica, 41(5): 1495-1511.]
- 陈雷,孙景贵,陈行时,等. 2009. 张广才岭东侧英城子金矿区花岗岩锆石 U-Pb 年龄及地质意义[J]. 地质学报, 83(9): 1327-1334. [Chen Lei, Sun Jingui, Chen Xingshi, et al. 2009. Zircon LA-ICP MS U-Pb dating of granite from the Yingchengzi gold deposit area in the eastern Zhangguangcailing area and its geological significance[J]. Acta Geologica Sinica, 83(9): 1327-1334.]
- 董策,周建波. 2012. 内蒙古东北部中二叠统哲斯组砂岩地球化学特征分析及物源区示踪[J]. 岩石矿物学杂志, 31(5): 663-673. [Dong Ce, Zhou Jianbo. 2012. Geochemical characteristics analysis and provenance tracing of sandstone in Middle Permian Zhesi Formation, northeast Inner Mongolia[J]. Acta Petrologica et Mineralogica, 31(5): 663-673.]
- 董玉. 2018. 佳木斯地块与松嫩—张广才岭地块拼合历史:年代学与地球化学证据[D]. 长春:吉林大学. [Dong Yu. 2018. Convergence history of the Jiamusi and Songnen-Zhangguangcai range massifs: Geochronological and geochemical evidence[D]. Changchun: Jilin University.]
- 冯连君,储雪蕾,张启锐,等. 2003. 化学蚀变指数(CIA)及其在新元古代碎屑岩中的应用[J]. 地学前缘, 10(4): 539-544. [Feng Lianjun, Chu Xuelei, Zhang Qirui, et al. 2003. CIA (chemical index of alteration) and its applications in the Neoproterozoic clastic rocks [J]. Earth Science Frontiers, 10(4): 539-544.]
- 傅寒晶,简星,梁杭海. 2021. 硅酸盐化学风化强度评估的沉积物指标与方法研究进展[J]. 古地理学报, 23(6): 1192-1209. [Fu Hanjing, Jian Xing, Liang Hanghai. 2021. Research progress of sediment indicators and methods for evaluation of silicate chemical weathering intensity[J]. Journal of Palaeogeography, 23(6): 1192-1209.]
- 葛文春,吴福元,周长勇,等. 2007. 兴蒙造山带东段斑岩型 Cu, Mo 矿床成矿时代及其地球动力学意义[J]. 科学通报, 52(20): 2407-2417. [Ge Wenchun, Wu Fuyuan, Zhou Changyong, et al. 2007. Porphyry Cu-Mo deposits in the eastern Xing'an-Mongolian Orogenic Belt: Mineralization ages and their geodynamic implications [J]. Chinese Science Bulletin, 52(20): 2407-2417.]
- 呼其图,关平,王大华,等. 2024. 柴达木盆地北缘东段中侏罗统物源分析:来自重矿物、元素地球化学及碎屑锆石年代学的证据[J]. 沉积学报, 42(2): 466-485. [Hu Qitu, Guan Ping, Wang Dahua, et al. 2024. Provenance analysis of the Middle Jurassic in northeastern Qaidam Basin: Evidence from heavy minerals, elemental geochemistry and detrital zircon U-Pb geochronology[J]. Acta Sedimentologica Sinica, 2024, 42(2): 466-485.]
- 靳立杰,王继林,周汉文,等. 2022. 东昆仑黑海地区赛什腾组变质碎屑岩地球化学特征及其对物质来源的制约[J]. 地质与勘探, 58(4): 778-786. [Jin Lijie, Wang Jilin, Zhou Hanwen, et al. 2022. Geochemical characteristics of the Serteng Formation metamorphic clastic rocks in the Heihai area of east Kunlun and their constraints on the provenance[J]. Geology and Exploration, 58(4): 778-786.]
- 冷宇坤,谢远云,康春国,等. 2023. 哈尔滨居仁砂砾石剖面沉积特征及其环境意义[J]. 沉积学报, 41(2): 472-484. [Leng Yukun, Xie Yuanyun, Kang Chunguo, et al. 2023. Sedimentary characteristics and environmental significance of the Juren sandy gravel profile in Harbin[J]. Acta Sedimentologica Sinica, 41(2): 472-484.]
- 李俊,赵红格,汪建,等. 2024. 鄂尔多斯盆地西缘中部三叠系延长组碎屑岩沉积环境及物源示踪[J]. 沉积学报, 42(5): 1621-1638. [Li Jun, Zhao Hongge, Wang Jian, et al. 2024. Sedimentary environment and provenance tracing of clastic rocks from the Triassic Yanchang Formation in the western margin of the Ordos Basin[J]. Acta Sedimentologica Sinica, 42(5): 1621-1638.]
- 李林林. 2018. 盆地沉积物源分析研究进展[J]. 地壳构造与地壳应力文集: 27-47. [Li Linlin. 2018. Research progress on basin sediment source analysis[J]. Collected Works on Crustal Structure and Crustal Stress: 27-47.]
- 李徐生,韩志勇,杨守业,等. 2007. 镇江下蜀土剖面的化学风化强度与元素迁移特征[J]. 地理学报, 62(11): 1174-1184. [Li Xusheng, Han Zhiyong, Yang Shouye, et al. 2007. Chemical weathering intensity and element migration features of the Xiashu loess profile in Zhenjiang[J]. Acta Geographica Sinica, 62(11): 1174-1184.]
- 李忠,王道轩,林伟,等. 2004. 库车坳陷中—新生代碎屑组相对物源类型及其构造属性的指示[J]. 岩石学报, 20(3): 655-666. [Li Zhong, Wang Daoxuan, Lin Wei, et al. 2004. Mesozoic-Cenozoic clastic composition in Kuqa Depression, Northwest China: Implication for provenance types and tectonic attributes[J]. Acta Petrologica Sinica, 20(3): 655-666.]
- 刘建峰,迟效国,董春艳,等. 2008. 小兴安岭东部早古生代花岗岩的发现及其构造意义[J]. 地质通报, 27(4): 534-544. [Liu Jianfeng, Chi Xiaoguo, Dong Chunyan, et al. 2008. Discovery of Early Paleozoic granites in the eastern Xiao Hinggan Mountains, northeastern China and their tectonic significance[J]. Geological Bulletin of China, 27(4): 534-544.]
- 刘军,毛景文,武广,等. 2013. 大兴安岭北部岔路口斑岩铜矿床岩浆锆石 U-Pb 年龄及其地质意义[J]. 地质学报, 87(2): 208-226. [Liu Jun, Mao Jingwen, Wu Guang, et al. 2013. Zircon U-Pb dating for the magmatic rocks in the Chalukou porphyry Mo deposit in the northern great Xing'an range, China, and its geological significance[J]. Acta Geologica Sinica, 87(2): 208-226.]
- 刘淑秋,杜乃秋,孔昭宸. 1985. 哈尔滨地区第四纪孢粉分析及其在地质学和植物学上的意义[J]. 植物研究, 5(4): 81-100. [Liu Shuqiu, Du Naiqiu, Kong Zhaochen. 1985. Palynoflora of the Quaternary from the Harbin Heilongjiang province and its significance in geology and botany[J]. Bulletin of Botanical Research, 5(4): 81-100.]
- 马明,陈国俊,吕成福,等. 2016. 珠江口盆地白云凹陷始新统一下渐新统沉积环境与泥岩物源[J]. 石油学报, 37(5): 610-621. [Ma Ming, Chen Guojun, Lü Chengfu, et al. 2016. Eocene-Low Oligo-

- cene sedimentary environment and mudstone provenance in Baiyun Sag, Pearl River Mouth Basin[J]. *Acta Petroli Sinica*, 37(5): 610-621.]
- 马英军,刘丛强. 1999. 化学风化作用中的微量元素地球化学:以江西龙南黑云母花岗岩风化壳为例[J]. *科学通报*, 44(22): 2433-2437. [Ma Yingjun, Liu Congqiang. 1999. Trace element geochemistry during chemical weathering: As exemplified by the weathered crust of granite, Longnan, Jiangxi[J]. *Chinese Science Bulletin*, 44(22): 2433-2437.]
- 缪振棣,初本君,高振操. 1984. 黑龙江省第四纪地层测年[J]. *地质论评*, 30(4): 357-364. [Miao Zhendi, Chu Benjun, Gao Zhencao. 1984. Dating of the Quaternary strata of Heilongjiang province[J]. *Geological Review*, 30(4): 357-364.]
- 彭治超,李亚男,张孙玄琦,等. 2018. 主微量元素地球化学特征在沉积环境中的应用[J]. *西安文理学院学报(自然科学版)*, 21(3): 108-111. [Peng Zhichao, Li Yanan, Zhangsun Xuanqi, et al. 2018. Application of the geochemical characteristics of the major and trace elements in the sedimentary environment[J]. *Journal of Xi'an University (Natural Science Edition)*, 21(3): 108-111.]
- 乔彦松,赵志中,王燕,等. 2010. 川西甘孜黄土—古土壤序列的地球化学演化特征及其古气候意义[J]. *科学通报*, 55(3): 255-260. [Qiao Yansong, Zhao Zhizhong, Wang Yan, et al. 2010. Variations of geochemical compositions and the paleoclimatic significance of a loess-soil sequence from Garzê county of western Sichuan province, China[J]. *Chinese Science Bulletin*, 55(3): 255-260.]
- 裘善文,夏玉海,汪佩芳,等. 1988. 松辽平原更新世地层及其沉积环境的研究[J]. *中国科学(B辑 化学 生物学 农学 医学 地学)*, 18(4): 431-441. [Qiu Shanwen, Xia Yuhai, Wang Peifang, et al. 1988. A study on the Pleistocene strata and their sedimentary environment in the Songliao Plain[J]. *Chinese Science (Part B)*, 18(4): 431-441.]
- 任永健. 2019. 张广才岭南部早—中侏罗世花岗质岩浆作用及构造演化[J]. *地质学报*, 93(11): 2813-2831. [Ren Yongjian. 2019. Early-Middle Jurassic granitic magmatism and tectonic evolution in the southern part of Zhangguangcailing[J]. *Acta Geologica Sinica*, 93(11): 2813-2831.]
- 石浩,岳大鹏,赵景波,等. 2022. 陕西绥德地区黄土—古土壤序列地球化学特征及其环境指示意义[J]. *地球与环境*, 50(1): 1-13. [Shi Hao, Yue Dapeng, Zhao Jingbo, et al. 2022. Geochemical characteristics of loess paleosol sequence and its environmental implications in Suide area, Shaanxi[J]. *Earth and Environment*, 50(1): 1-13.]
- 宋立军,刘池阳,赵红格,等. 2016. 鄂尔多斯地区黄旗口组地球化学特征及其沉积环境与构造背景[J]. *地球科学*, 41(8): 1295-1308. [Song Lijun, Liu Chiyang, Zhao Hongge, et al. 2016. Geochemical characteristics, sedimentary environment and tectonic setting of Huangqikou Formation, Ordos Basin[J]. *Earth Science*, 41(8): 1295-1308.]
- 孙德有,吴福元,高山. 2004. 小兴安岭东部清水岩体的锆石激光探针 U-Pb 年龄测定[J]. *地球学报*, 25(2): 213-218. [Sun Deyou, Wu Fuyuan, Gao Shan. 2004. LA-ICPMS zircon U-Pb age of the Qingshui pluton in the East Xiao Hinggan mountains[J]. *Acta Geoscientia Sinica*, 25(2): 213-218.]
- 孙德有,吴福元,李惠民,等. 2000. 小兴安岭西北部造山后 A 型花岗岩的时代及与索伦山—贺根山—扎赉特碰撞拼合带东延的关系[J]. *科学通报*, 45(20): 2217-2222. [Sun Deyou, Wu Fuyuan, Li Huimin, et al. 2000. Emplacement age of the postorogenic A-type granites in northwestern Lesser Xing'an Ranges, and its relationship to the eastward extension of Suolushan-Hegenshan-Zhalaithe collisional suture zone[J]. *Chinese Science Bulletin*, 45(20): 2217-2222.]
- 孙建中. 2005. 黄土学(上篇)[M]. 香港:香港考古学会:354-366. [Sun Jianzhong. 2005. *Loess science (Part I)*[M]. Hong Kong, China: Hong Kong Archaeological Society: 354-366.]
- 孙磊. 2023. 松嫩平原东部罗家窝棚组地层特征、沉积环境及其区域地质意义[D]. 哈尔滨:哈尔滨师范大学. [Sun Lei. 2023. *Stratigraphic characteristics, sedimentary environment and regional geological significance of Luojiawopeng Formation in eastern Songnen Plain*[D]. Harbin: Harbin Normal University.]
- 王恩宝. 2012. 哈尔滨地区第四纪沉积序列及其环境意义[D]. 长春:吉林大学. [Wang Enbao. 2012. *Quaternary sedimentary sequences and their environmental significance in Harbin area*[D]. Changchun: Jilin University.]
- 王久懿,孙彦峰,周传芳,等. 2023. 黑龙江漠河盆地漠河组砂岩碎屑锆石 U-Pb 年龄、地球化学特征及其对构造背景的制约[J]. *地质通报*, 42(1): 146-167. [Wang Jiuyi, Sun Yanfeng, Zhou Chuanfang, et al. 2023. Detrital zircon U-Pb age and geochemistry of sandstone from the Mohe Formation in the Mohe Basin, Heilongjiang and their constraints on tectonic setting[J]. *Geological Bulletin of China*, 42(1): 146-167.]
- 王昆山,石学法,刘升发,等. 2014. 泰国湾西部表层沉积物重矿物分布特征:对物质来源和沉积环境的指示[J]. *第四纪研究*, 34(3): 623-634. [Wang Kunshan, Shi Xuefa, Liu Shengfa, et al. 2014. Spatial distribution of heavy minerals in the surface sediments from the western gulf of Thailand: Implications for sediment provenance and sedimentary environment[J]. *Quaternary Sciences*, 34(3): 623-634.]
- 魏春艳,谢远云,康春国,等. 2022. 哈尔滨地区罗家窝棚组地层的沉积学、矿物学及地球化学特征:对沉积环境的指示[J]. *地质科学*, 57(1): 172-189. [Wei Chunyan, Xie Yuanyun, Kang Chunguo, et al. 2022. Sedimentological, mineralogical, and geochemical characteristics of the Luojiawopeng Fm. in Harbin: Implications for the sedimentary environment[J]. *Chinese Journal of Geology*, 57(1): 172-189.]
- 吴金城,叶启晓,刘文. 1984. 黑龙江省哈尔滨(荒山、顾乡屯)地区第四纪地质研究:专题科研报告[DS]. 全国地质资料馆. [Wu Jincheng, Ye Qixiao, Liu Wen. 1984. *Quaternary geological research in Harbin (barren hills and Guxiangtun) area, Heilongjiang province: Special scientific research report* [DS]. National Geological Archive.]

- 吴年冬,王忠伟,倪战旭,等. 2020. 桂东大桂山地区寒武系砂岩地球化学特征及沉积构造环境分析[J]. 桂林理工大学学报, 40(4): 655-664. [Wu Niandong, Wang Zhongwei, Ni Zhanxu, et al. 2020. Geochemical characteristics and sedimentary-tectonic settings of Cambrian sandstone in Daguishan area, eastern Guangxi [J]. Journal of Guilin University of Technology, 40(4): 655-664.]
- 吴子杰,张国仁,邱隆伟,等. 2024. 辽宁新元古界桥头组砂岩地球化学特征及其沉积背景[J]. 中国地质, 51(5): 1714-1726. [Wu Zijie, Zhang Guoren, Qiu Longwei, et al. 2024. Geochemical characteristics of sandstone and sedimentary background of Neoproterozoic Qiaotou Formation in Liaoning[J]. Geology in China, 51(5): 1714-1726.]
- 徐杰,姜在兴. 2019. 碎屑岩物源研究进展与展望[J]. 古地理学报, 21(3): 379-396. [Xu Jie, Jiang Zaixing. 2019. Provenance analysis of clastic rocks: Current research status and prospect[J]. Journal of Palaeogeography, 21(3): 379-396.]
- 徐小涛,邵龙义. 2018. 利用泥质岩化学蚀变指数分析物源区风化程度时的限制因素[J]. 古地理学报, 20(3): 515-522. [Xu Xiaotao, Shao Longyi. 2018. Limiting factors in utilization of chemical index of alteration of mudstones to quantify the degree of weathering in provenance[J]. Journal of Palaeogeography, 20(3): 515-522.]
- 杨浩,葛文春,纪政,等. 2022. 中国东北地区中生代岩浆作用和洋—陆格局及其与气候演变的关系[J]. 岩石学报, 38(5): 1443-1459. [Yang Hao, Ge Wenchun, Ji Zheng, et al. 2022. Phanerozoic magmatism and ocean-continent framework of northeastern China and their relationship with climate change[J]. Acta Petrologica Sinica, 38(5): 1443-1459.]
- 叶启晓. 1991. 哈尔滨地区第四系[J]. 黑龙江地质, 2(2): 17-29. [Ye Qixiao. 1991. Quaternary system in Harbin area[J]. Heilongjiang Geology, 2(2): 17-29.]
- 叶启晓,吴金城,魏正一. 1984. 哈尔滨荒山近期的上升运动[J]. 地理科学, 4(4): 383-388. [Ye Qixiao, Wu Jincheng, Wei Zhengyi. 1984. The tectonic uplift occurred in Huang Shan in the last thousands of year[J]. Scientia Geographica Sinica, 4(4): 383-388.]
- 张国宾,陈兴凯,赵越,等. 2022. 张广才岭南部中侏罗世似斑状二长花岗岩年代学、地球化学特征及其地质意义[J]. 吉林大学学报(地球科学版), 52(6): 1907-1925. [Zhang Guobin, Chen Xing kai, Zhao Yue, et al. 2022. Geochronology, geochemistry and geological significance of the Middle Jurassic porphyritic monzogranite in the southern Zhangguangcai range, Heilongjiang province[J]. Journal of Jilin University (Earth Science Edition), 52(6): 1907-1925.]
- 张衡,李仁涛,巴金,等. 2019. 川西南美姑地区下三叠统飞仙关组地球化学特征及其对物源和构造环境的指示意义[J]. 矿物岩石, 39(3): 52-59. [Zhang Heng, Li Rentao, Ba Jin, et al. 2019. Geochemical characteristics of the Lower Triassic Feixianguan Formation in Meigu area, southwestern Sichuan and its significance for the provenance and tectonic setting[J]. Journal of Mineralogy and Petrology, 39(3): 52-59.]
- 张立仕,孙丰月,李碧乐,等. 2021. 小兴安岭—张广才岭成矿带福安堡铜矿区花岗岩类的岩石成因和构造背景:元素地球化学、锆石 U-Pb 年龄和 Sr-Nd-Hf 同位素约束[J]. 地质学报, 95(8): 2471-2492. [Zhang Lishi, Sun Fengyue, Li Bile, et al. 2021. Petrogenesis and tectonic setting of granitoids in the Fu'anpu molybdenum deposit, Lesser Xing'an-Zhangguangcai Range metallogenic belt: Constraints from element geochemistry, zircon U-Pb geochronology and Sr-Nd-Hf isotopes[J]. Acta Geologica Sinica, 95(8): 2471-2492.]
- 张曼. 2021. 哈尔滨荒山岩芯黄土—古土壤序列的化学风化特征及其对古土壤形成环境指示[D]. 哈尔滨:哈尔滨师范大学. [Zhang Man. 2021. Chemical weathering characteristics of the loess-paleosol sequence in Harbin Huangshan rock core and implication for formation environment of the paleosol[D]. Harbin: Harbin Normal University.]
- 张茜,肖渊甫,王晓飞,等. 2020. 四川盆地西南缘龙马溪组泥岩地球化学特征及物源区和构造背景分析[J]. 地质论评, 66(5): 1393-1411. [Zhang Qian, Xiao Yuanfu, Wang Xiaofei, et al. 2020. Geochemistry of the Longmaxi Formation mudstones of the southwest Sichuan Basin: Implications for provenance and source weathering [J]. Geological Review, 66(5): 1393-1411.]
- 张英利,贾晓彤,王宗起,等. 2019. 上扬子西南缘早三叠世嘉陵江组物源分析和构造环境:沉积学、重矿物电子探针和 U-Pb 年龄的限定[J]. 地质学报, 93(12): 3197-3222. [Zhang Yingli, Jia Xiaotong, Wang Zongqi, et al. 2019. Provenance analysis and tectonic setting of Early Triassic Jialingjiang Formation in the southwestern Upper Yangtze area: Evidence from sedimentology, heavy mineral electron probe microanalysis and U-Pb dating[J]. Acta Geologica Sinica, 93(12): 3197-3222.]
- Andersen T, van Niekerk H, Elburg M A. 2022. Detrital zircon in an active sedimentary recycling system: Challenging the 'source-to-sink' approach to zircon-based provenance analysis[J]. Sedimentology, 69(6): 2436-2462.
- Armstrong-Altrin J S. 2020. Detrital zircon U-Pb geochronology and geochemistry of the Riachuelos and Palma Sola beach sediments, Veracruz State, Gulf of Mexico: A new insight on palaeoenvironment[J]. Journal of Palaeogeography, 9(1): 28.
- Armstrong-Altrin J S, Machain-Castillo M L. 2016. Mineralogy, geochemistry, and radiocarbon ages of deep sea sediments from the Gulf of Mexico, Mexico[J]. Journal of South American Earth Sciences, 71: 182-200.
- Bhatia M R. 1985. Rare earth element geochemistry of Australian Paleozoic graywackes and mudrocks: Provenance and tectonic control[J]. Sedimentary Geology, 45(1/2): 97-113.
- Bhatia M R, Crook K A W. 1986. Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins [J]. Contributions to Mineralogy and Petrology, 92(2): 181-193.
- Bhatia M R, Taylor S R. 1981. Trace-element geochemistry and sedimentary provinces: A study from the Tasman Geosyncline, Australia [J]. Chemical Geology, 33(1/2/3/4): 115-125.
- Cox R, Lowe D R, Cullers R L. 1995. The influence of sediment recycling and basement composition on evolution of mudrock chemis-

- try in the southwestern United States[J]. *Geochimica et Cosmochimica Acta*, 59(14): 2919-2940.
- Fedo C M, Nesbitt H W, Young G M. 1995. Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance[J]. *Geology*, 23(10): 921-924.
- Floyd P A, Leveridge B E. 1987. Tectonic environment of the Devonian Gramscatho Basin, south Cornwall: Framework mode and geochemical evidence from turbiditic sandstones[J]. *Journal of the Geological Society*, 144(4): 531-542.
- Griffin W L, Belousova E A, Shee S R, et al. 2004. Archean crustal evolution in the northern Yilgarn Craton: U-Pb and Hf-isotope evidence from detrital zircons[J]. *Precambrian Research*, 131(3/4): 231-282.
- Gu X X, Liu J M, Zheng M H, et al. 2002. Provenance and tectonic setting of the Proterozoic turbidites in Hunan, South China: Geochemical evidence[J]. *Journal of Sedimentary Research*, 72(3): 393-407.
- Jones B, Manning D A C. 1994. Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones[J]. *Chemical Geology*, 111(1/2/3/4): 111-129.
- Maharana C, Srivastava D, Tripathi J K. 2018. Geochemistry of sediments of the Peninsular rivers of the Ganga Basin and its implication to weathering, sedimentary processes and provenance[J]. *Chemical Geology*, 483: 1-20.
- McLennan S M, Hemming S, McDaniel D K, et al. 1993. Geochemical approaches to sedimentation, provenance, and tectonics[M]//Johnson M J, Basu A. Processes controlling the composition of clastic sediments. Boulder: Geological Society of America: 21-40.
- Muhs D R. 2004. Mineralogical maturity in dunefields of North America, Africa and Australia[J]. *Geomorphology*, 59(1/2/3/4): 247-269.
- Nesbitt H W, Young G M. 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites[J]. *Nature*, 299(5885): 715-717.
- Nesbitt H W, Young G M. 1989. Formation and diagenesis of weathering profiles[J]. *The Journal of Geology*, 97(2): 129-147.
- Nesbitt H W, Young G M, McLennan S M, et al. 1996. Effects of chemical weathering and sorting on the petrogenesis of siliciclastic sediments, with implications for provenance studies[J]. *The Journal of Geology*, 104(5): 525-542.
- Parker A. 1970. An index of weathering for silicate rocks[J]. *Geological Magazine*, 107(6): 501-504.
- Parrish J T. 1980. Lakes: Chemistry, geology, physics. A. Lerman[J]. *The Journal of Geology*, 88(2): 249-250.
- Roser B P, Korsch R J. 1988. Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data[J]. *Chemical Geology*, 67(1/2): 119-139.
- Suttner L J, Dutta P K. 1986. Alluvial sandstone composition and paleoclimate; I, Framework mineralogy[J]. *Journal of Sedimentary Research*, 56(3): 329-345.
- Taylor S R, McLennan S M. 1985. The continental crust: Its composition and evolution: An examination of the geochemical record preserved in sedimentary rocks[M]. Oxford: Blackwell Scientific.
- Weltje G J, von Eynatten H. 2004. Quantitative provenance analysis of sediments: Review and outlook[J]. *Sedimentary Geology*, 171(1/2/3/4): 1-11.
- Zheng H B, Clift P D, He M Y, et al. 2020. Formation of the first bend in the Late Eocene gave birth to the modern Yangtze River, China [J]. *Geology*, 49(1): 35-39.

Stratigraphic Attribute Characteristics of Sand and Gravel Accumulation of Sanjiedi Profile in Harbin, China

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Abstract: [Objective] The sand and gravel in the Sanjie area of Juren town, Bin county, Heilongjiang province, was once considered as the lower limit of the Quaternary Luojiaowopeng Formation in the Harbin area, but research on its stratigraphic properties and sedimentary environment has been relatively poor to date. This has greatly limited the

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in-depth understanding of the regional surface processes recorded in this stratum. **[Methods]** To discuss and compare the sedimentary environment and stratigraphic division, this study adopted a range of research methods. Sedimentology, mineralogy, elemental geochemistry and detrital zircon U-Pb chronology were used to investigate the chemical weathering characteristics, source rock properties, sedimentary environment and structural background of the source area in this section to determine the effects of chemical weathering, sedimentary cycles and material sources, and to explore the structural background and indicators of stratigraphic delineation and regional magmatic tectonic events. **[Results]** It was found that the sediment in the three sections is mainly composed of brownish-yellow sand and gravel mixed with muddy interlayers, with local oblique bedding. The weathering degree of the sand and gravel is low, the sorting is moderate, the roundness is good, and there is no obvious directional arrangement. The gravel rock is mainly granite (46.31%) and quartzite (28.19%), with some syenite (0.2%), tuff (0.01%) and schist (0.01%). The heavy minerals are mainly spinel (65.18%) and epidote (11.87%), with minor quantities of zircon (2.28%), apatite (5.60%), ilmenite (2.77%), hematite (3.41%) and magnetite (5.15%); white titanium (0.54%) and pyrrhotite (0.1%) account for less than 1%, and other heavy minerals account for 3.11%. Elemental geochemical analysis revealed that the fine-grained components in the sediments have experienced weak to moderate chemical weathering, and most have undergone initial weathering cycles. Gravel lithology and geochemical composition indicate that the parent rock of the sediments was mainly medium- to acidic magma. The geochemistry of the migration and enrichment of elements in the sediments, paleoclimate discrimination diagrams and sedimentary facies definition indicate that the regional environment of the sediments was a meandering river that transported the sediments over short distances in an arid oxidative environment. The distribution range of detrital zircon U-Pb ages is relatively narrow (134.2-220.3 Ma, peaking at about 168 Ma). Comparison of the zircon ages of the surrounding potential source areas together with their geomorphological location suggests the detrital contribution of the Zhangguangcai Ridge and indicates the collision and assembly of the Jiamusi and Songnen Blocks, as well as the continuous subduction of the eastern oceanic plate. Significant differences were found between the three sections in terms of their sedimentological characteristics, genetic types and geomorphological features when compared with the standard strata of the Luojiawopeng Formation. It is speculated that formation of the three sections was roughly contemporaneous with the formation time of the Baitushan Formation in western Harbin. **[Conclusions]** This study is of great significance for the reconstruction of geological events such as Quaternary stratigraphic divisions and Upper Jurassic tectonic geomorphological-climate-water system evolution in the Harbin area.

Key words: Sanjiedi profile; geochemistry; zircon U-Pb dating; provenance; sedimentary environment; stratigraphic division