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## 河北宣化土城子组恐龙足迹赋存层位厘定、 沉积演化与凝灰岩年代学约束

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**摘要:**【研究目的】河北宣化地区土城子组发现大量恐龙足迹, 不仅为研究和恢复土城子组沉积期古生态, 特别是恐龙动物群的古生态与古地理环境提供了极其珍贵的基础素材, 同时也具有十分重要的科学意义和研究价值。尽管前期国内外发表了多篇与此相关的研究成果, 但有关恐龙足迹在土城子组中的地层层位、沉积序列和沉积环境, 以及年代学等研究仍存在较大分歧。【研究方法】在详细野外地质调查的基础上, 通过地层学、沉积学、综合分析与研究等方法, 对宣化立石村保存恐龙足迹的土城子组进行了系统研究和讨论。【研究结果】结果显示, 宣化立石村土城子组垂向上可划分为 4 个段, 恐龙足迹并非发育于第一段, 而是产于第四段底部粉砂岩和细砂岩韵律中, 并自下而上形成 2 个“滨浅湖—辫状河—洪积扇”沉积旋回层序。【结论】综合沉积物结构构造等证据表明, 恐龙足迹形成于浅水甚至间歇性暴露的河流相河漫滩的沉积环境; 宣化土城子组恐龙足迹上覆凝灰岩锆石 U-Pb 年龄为 155~142 Ma, 推测其可能形成于晚侏罗世早期—早白垩世早期。

**关键词:** 恐龙足迹; 地层层位; 沉积环境; 凝灰岩及定年; 土城子组; 河北宣化

**创新点:** 采用系统地层和沉积学调查研究方法, 重新将宣化地区土城子组划分为 4 个段, 提出恐龙足迹赋存于四段下部, 也即整个土城子组层序中上部而非底部, 形成于河流相河漫滩沉积环境; 恐龙足迹上覆凝灰岩锆石 U-Pb 年龄为 155~142 Ma, 表明其可能形成于晚侏罗世早期—早白垩世早期。

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## Stratigraphic horizon determination, sedimentary evolution, and tuff geochronology of dinosaur footprint-bearing strata in the Tuchengzi Formation, Xuanhua, Hebei Province

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**Abstract: [Objective]** Recently, a large number of dinosaur footprints have been discovered in the Tuchengzi Formation in Xuanhua

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District, Hebei Province, which not only provides extremely valuable basic materials for the study and restoration of the paleoecology of the Tuchengzi Formation, especially the paleoecology and paleogeographic environment of the dinosaur fauna, but also shows very important scientific significance and research value. Although many related research results have been published at home and abroad, there are great controversial about the stratigraphic depositional sequence, sedimentary environment and chronology of horizon of dinosaur footprints in the Tuchengzi Formation. **[Methods]** On the basis of detailed field geological investigation, the paper systematically studied and discussed the Tuchengzi Formation where dinosaur footprints were preserved in Lishi County, Xuanhua through stratigraphy, sedimentology and comprehensive analysis. **[Results]** In this study, the Tuchengzi Formation of Lishi County in Xuanhua is divided into four members vertically, and the dinosaur footprints are not developed in the first member as previous people supposed, but in the siltstone and fine sandstone rhythm at the bottom of the forth members, and form two sedimentary cyclic sequences of "shallow lake-braided river-alluvial fan" from bottom to top. **[Conclusions]** Comprehensive evidence, encompassing sedimentary structures and tectonic features, suggests that the dinosaur footprints originated in a sedimentary setting characterized by shallow water or intermittently exposed floodplains of fluvial facies. The zircon U-Pb dating of the tuff overlying the dinosaur footprints within the Tuchengzi Formation in Xuanhua indicates an age range of 155~142 Ma, implying that these footprints likely formed from the early stage of the Late Jurassic to the early stage of the Early Cretaceous.

**Key words:** dinosaur track; stratigraphic sequence; sedimentary environment; tuff and dating; Tuchengzi Formation; Xuanhua, Hebei Province

**Highlights:** Employing systematic stratigraphic and sedimentological research methods, the Tuchengzi Formation in the Xuanhua region has been reclassified into four distinct members. It is suggested that dinosaur footprints are found in the lower section of the fourth member, specifically in the upper-middle stratum of the entire Tuchengzi Formation sequence, rather than at its base, and were formed within a fluvial floodplain depositional environment. The zircon U-Pb dating of the tuff overlying these footprints indicates an age range of 155~142 Ma, suggesting their formation during the early part of the Late Jurassic to the early part of the Early Cretaceous epoch.

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冀北—辽西地区广泛发育侏罗纪—白垩纪过渡期的陆相红色碎屑沉积岩系—土城子组, 其是侏罗纪—白垩纪过渡时期的地层记录。几十年来, 很多学者对土城子组古生物、地层与沉积序列、沉积环境等进行了深入研究(王思恩, 1989, 2013; 和政军等, 1998, 2007, 2008; 郑少林, 2000; 柳永清等, 2002, 2003, 2009, 2012; 贾建称等, 2003; 邵济安等, 2003; 翟明国等, 2003; 刘少峰等, 2004; 王五力等, 2004; 张永忠等, 2004; Davis, 2005; 季强等, 2006; 渠洪杰等, 2006; 孙立新等, 2007; 张宏等, 2008; 柯舒文等, 2009; 许欢等, 2011, 2013, 2014, 2016; 刘晓波等, 2016; 王大宁等, 2016; 贺瑾瑞等, 2020; 万晓樵等, 2020)。土城子组发育于侏罗纪—白垩纪过渡期, 该时期是中国华北及东北地区中一晚侏罗世燕辽生物群与早白垩世热河生物群过渡时期。但由于土城子组陆相红层粗碎屑岩系中无脊椎及脊椎动物化石匮

乏, 导致对上述 2 个生物群演化(过渡)关系及侏罗纪—白垩纪过渡期的古地理、古生态环境的了解不深入。仅根据土城子组的陆相红层、孢粉学及风成沉积与大干旱事件研究认为, 华北侏罗纪—白垩纪过渡期气候炎热干旱, 为植被稀少的“荒原环境”, 可能是造成燕辽生物群消亡的主要因素(Xu et al., 2017; Yi et al., 2019)。然而, 华北侏罗纪—白垩纪过渡期陆相红层中陆续发现恐龙、鸟类或翼龙类的足迹(李日辉等, 2002; 柳永清等, 2002, 2003, 2012; Lockley et al., 2006; 张建平等, 2012; Xing et al., 2015, 2020, 2021a, b, 2023; Xu et al., 2018, 2021; 鞠书彬等, 2022; 李兴文等, 2024, 2026; 唐永忠等, 2026), 导致人们质疑之前认为的侏罗纪—白垩纪过渡期的“荒原环境”可能并非是无生机, 而是繁盛着以恐龙为代表的脊椎动物群, 甚至可能构成了时空分布广、生物多样性高、赋存环境多样的生物群与生

Fig. 1 Distributions of the Tuchengzi Formation and dinosaur tracks in Yanliao area (a) and the Dinosaur tracks distribution in southern Xuanhua area (b)

大青山组),下白垩统张家口组(满克头鄂博组、玛尼吐组、白音高老组),大北沟组、义县组,九佛堂组(西瓜园组),阜新组、沙海组和上白垩统孙家湾组。其中,土城子组主要指介于中上侏罗统髫髻山组(含九龙山组)和下白垩统张家口组(或义县组)之间的一套陆相红色碎屑沉积岩系。

过去几十年来土城子组古生物地层方面的研究取得了诸多进展。如土城子组内发育植物大化石、孢粉、介形类、叶肢介、昆虫等化石(王五力等, 2004; 王思恩等, 2013)。尽管宣化地区土城子组二段曾发现了 4 件不完整的角龙类化石标本,并建立了角龙类一新属种——聂氏宣化角龙(Zhao et al., 2006),但华北土城子组中很少见到脊椎动物骨骼化石。此外,还有少量关于恐龙足迹化石的报道。如 1940 年, Yabe et al. (1940)报道了辽宁朝阳羊山地区土城子组的 4000 余枚蹠脚龙足迹。诸多学者在辽西朝阳、北票,冀北承德、赤城、尚义,以及北京延庆等地的土城子组中发现大量的恐龙足迹、游泳迹和疑似的蹲伏迹化石(张永忠等, 2004; Sullivan et al., 2009; Xing et al., 2009, 2012; 柳永清等, 2012; 张建平, 2012; 何情等, 2015),此外还包括古鸟类足迹化石(Lockley et al., 2006)。频繁发现的大量兽脚类、鸟脚类及蜥脚类恐龙足迹(群)暗示,土城子组/后城组沉积期应发育以恐龙动物群为代表的陆地脊椎动物群。深入分析和对比恐龙动物群(骨骼化石)和足迹的发育特征与规律,对于研究晚侏罗世—早白垩世恐龙动物群的组成和生活习性、古地理环境,乃至恐龙的分布与迁徙都具有极其重大的科学意义。土城子组测年不仅可以约束土城子组的时代,也可以限制该组中的恐龙等动植物群的时代问题。基于土城子组大量同位素年龄数据研究结果(Cope, 2003, 2007; 柳永清, 2003; 刘健等, 2006; 杨蔚, 2007; Xu et al., 2012),认为该组底界为 154~153 Ma。同时,冀北—辽西土城子组的年代学研究将该组顶界置于 137~136 Ma 之间(张宏等, 2008; 许欢等, 2012, 2014, 2018; 王思恩等, 2013)。而以往对土城子组恐龙等足迹的研究还指示它们大部分发育在土城子组三段(Yabe et al., 1940; 张永忠等, 2004; Lockley et al., 2006; Sullivan et al., 2009; Xing et al., 2009, 2012; 柳永清等, 2012; 张建平, 2012)。因此,如果属实,那么燕山冀北—辽西地区就发育着庞大的、略老于 137~136 Ma,并以恐龙为主的陆相脊椎动物群。

2021 年,宣化地区土城子组也发现大规模和批量发育的恐龙足迹,其集中分布于宣化县立石村—姚家坡—东寺沟一带,呈近 NNW 向展布,主要赋存于土城子组四段下部河流相沉积的粉细砂岩层面之上,岩性为灰色—灰绿色泥质粉砂岩,自北向南可划分为 7 个足迹产地(图 1-b)。然而,对于宣化产出恐龙足迹层的时代,朱本鸿等(2020)依据足迹层上覆凝灰岩 142 Ma 的定年数据将其归属于早白垩世张家口组;而 Xing et al. (2021)、鞠书彬等(2022)和贡杰等(2022a)分别获得 155 Ma、152.3 Ma 和 153.2 Ma 的定年数据,这与北京延庆千家店盆地土城子组恐龙足迹定年结果(157 Ma)相近(贺瑾瑞等, 2017)。

对比分析可知,前期文献研究成果和新近宣化土城子组恐龙足迹化石的层位及定年时代出现了极大的矛盾和分歧。那么究竟冀北—辽西土城子组恐龙足迹化石(动物群)是否可以对比?时代是否相近?是否属于同一层位?或者进一步说,土城子组沉积期是否存在不同、还是相同时期(老、新种群)的恐龙等动物群?本文针对上述重要成果认识的分歧问题,基于详细的地质调查和剖面测制,重点研究和建立宣化恐龙足迹产地土城子组的完整地层层序和沉积序列,进而分析沉积环境和系统梳理前期定年研究中的足迹层上覆凝灰岩测年数据,最终开展区域性对比研究工作,厘定宣化赋存恐龙足迹的土城子组完整的地层层序、沉积序列、沉积环境和时代,为研究探索土城子组沉积期以恐龙动物群为代表的陆地脊椎动物群古地理、古生态环境和时空演化提供扎实的基础资料和数据。本次研究对认识华北北部晚侏罗世—早白垩世的恐龙动物群辐射或演化关系等地质科学问题具有重大意义。

## 2 材料和研究方法

首先开展宣化地区系统的区域地质调查,追索土城子组的空间分布、顶底界线、接触关系和土剖面实测,运用岩石地层学、沉积学、古生物地层学等方法与手段,依据详细地层层序、沉积构造和沉积序列描述,识别沉积相,研究沉积环境,同时研究恐龙足迹在土城子组的精确层位,特别关注和确定足迹和上覆凝灰岩的接触关系,土城子组中凝灰岩的发育层位、层数与前人测年样品的对应关系,最终建立起土城子组的层序和沉积序列,研究沉积相和沉积环境的发育及演化规律,分析梳理土城子组恐龙足迹

上覆同位素定年数据, 进一步开展区域对比, 厘定土城子组恐龙足迹代表的恐龙动物群时空发育和地层、沉积与年代格架。

## 2.1 实测剖面

研究区土城子组广泛分布于宣化区罗家洼—东寺沟、龙门堡—立石村—姚家坡一带, 其中以立石村附近露头最好, 顶、底出露齐全, 与下伏和上覆地层接触关系也较清晰(图 2)。实测剖面起点坐标为北纬 40°26'59"、东经 114°58'35", 终点坐标为北纬 40°25'35"、东经 114°56'20", 剖面总厚度 721.54 m, 具体描述如下。

|                                                                                      |                  |
|--------------------------------------------------------------------------------------|------------------|
| 四段 ( $J_3tch^4$ )                                                                    | 厚 323.23 m (未见顶) |
| 56. 砖红色砾岩, 分选性差                                                                      | 88.59 m          |
| 55. 浅灰绿色、浅粉色流纹质角砾凝灰岩 (第 2 层凝灰岩)                                                      | 25.31 m          |
| 54. 砖红色厚—块层砾岩, 砾石成分复杂, 分选性差 (图 3-h), 偶见恐龙足迹                                          | 122.27 m         |
| 53. 灰紫色中厚层砾岩夹少量泥岩透镜体                                                                 | 43.99 m          |
| 52. 灰白色—浅灰绿色蒙脱石化角砾凝灰岩 (Xing et al., 2021; 朱本鸿等, 2020; 鞠书彬等, 2022 测年样品采集层位, 第 1 层凝灰岩) | 18.14 m          |
| 51. 灰紫色中厚层细砂岩, 层面恐龙足迹 (Xing et al., 2021; 鞠书彬等, 2022) 和木化石                           | 4.93 m           |
| 50. 灰色砾岩, 整合于三段泥质粉砂岩之上                                                               | 1.10 m           |
| 三段 ( $J_3tch^3$ )                                                                    | 厚 113.70 m       |
| 49. 紫红色泥质粉砂岩与灰绿色砂岩互层, 水平层理发育, 层面上见虫迹化石和泥裂                                            | 19.47 m          |
| 48. 浅灰紫色厚层粗中粒长石岩屑砂岩夹少量紫红色中层粉砂岩, 后者层面见大量虫迹化石 (图 3-b)                                  | 6.53 m           |
| 47. 紫红色薄层粉砂岩, 局部夹泥质粉砂岩条带                                                             | 7.07 m           |
| 46. 灰绿色、绿色粉砂质页岩, 产少量植物化石碎片                                                           | 3.34 m           |
| 45. 灰色、灰绿色中厚层中砂岩、含砾中砂岩与紫红色泥质粉砂岩互层                                                    | 25.77 m          |
| 44. 砖红色中薄层细砂岩与紫红色薄层粉砂岩                                                               | 5.98 m           |
| 43. 灰紫色粉砂岩, 其中含大量钙质结核                                                                | 9.33 m           |
| 42. 砖红色细砂岩夹灰绿色粉砂岩条带, 整合于二段含砾粗砂岩之上                                                    | 36.21 m          |
| 二段 ( $J_3tch^2$ )                                                                    | 厚 189.11 m       |
| 41. 灰色中层砾质粗砂岩、含砾粗砂岩夹紫红色细砂岩, 局部见大量泥砾                                                  | 27.81 m          |
| 40. 灰色砾岩夹透镜体状砂岩, 砾石以变质岩、安山岩                                                          |                  |

|                                                          |            |
|----------------------------------------------------------|------------|
| 为主                                                       | 12.70 m    |
| 39. 砖红色薄层细砂岩                                             | 1.20 m     |
| 38. 灰绿色、灰色含砾粗砂岩夹灰紫色砾岩透镜体                                 | 8.00 m     |
| 37. 紫红色细砂岩夹灰绿色泥质条带                                       | 7.20 m     |
| 36. 灰紫色砾岩夹砂岩透镜体, 砾石以变质岩、安山岩为主, 白云岩次之                     | 19.30 m    |
| 35. 砖红色粉砂岩夹少量砂岩透镜体                                       | 5.60 m     |
| 34. 砖红色细砂岩与灰绿色中粗粒砂岩互层, 向上细砂岩变薄                           | 2.00 m     |
| 33. 灰黄色、灰褐色含砾粗砂岩, 交错层理发育                                 | 1.50 m     |
| 32. 灰紫色厚层粗砂岩与薄层含砾粗砂岩互层                                   | 3.40 m     |
| 31. 砖红色泥质粉砂岩夹灰绿色中层中细粒长石石英砂岩透镜体                           | 4.50 m     |
| 30. 紫灰色粉砂—细砂岩                                            | 1.50 m     |
| 29. 灰色、浅灰紫色砾岩, 砾石成分以变质岩为主, 次圆状—圆状                        | 0.90 m     |
| 28. 灰色中薄层砂岩, 发育平行层理                                      | 0.80 m     |
| 27. 灰色砾岩, 砾石以变质岩为主, 白云岩、安山岩次之                            | 1.00 m     |
| 26. 灰色中层含砾粗砂岩, 发育交错层理                                    | 1.50 m     |
| 25. 紫红色含砾粗砂岩夹砖红色粉砂质泥岩透镜体                                 | 6.50 m     |
| 24. 浅紫色块层含砾中粗砂岩, 砾石以白云岩、片麻岩为主                            | 8.90 m     |
| 23. 灰紫色粗砂岩夹砖红色泥质粉砂岩透镜体, 向上泥质含量增加                         | 23.60 m    |
| 22. 紫红色、砖红色粉砂岩                                           | 5.30 m     |
| 21. 灰色粗砂岩夹薄层细砾岩, 发育板状交错层理, 砂岩内含泥砾                        | 8.60 m     |
| 20. 砖红色薄层粉砂岩, 含少量泥质成分                                    | 2.90 m     |
| 19. 紫灰色中厚层含砾粗砂岩, 平行层理、交错层理发育                             | 9.60 m     |
| 18. 紫红色砖红色细砂岩夹泥质粉砂岩条带                                    | 4.40 m     |
| 17. 灰色、浅灰色含砾粗砂岩, 发育交错层理                                  | 3.00 m     |
| 16. 砖红色泥质粉砂岩                                             | 10.90 m    |
| 15. 灰色中层含砾粗砂岩夹砾岩透镜体, 整合于一段泥质粉砂岩之上, 发育大型槽状、板状交错层理 (图 3-c) | 7.10 m     |
| 一段 ( $J_3tch^1$ )                                        | 厚 115.50 m |
| 14. 紫红色泥质粉砂岩, 水层层理发育 (图 3-a)                             | 23.70 m    |

13. 紫灰色砾岩, 砾石以安山岩为主, 次棱角状—次圆状 4.00 m
12. 砖红色含砾粗砂岩, 砾石一般 0.2~2 cm, 成分复杂。该层被安山玢岩脉侵入, 后者大致呈近顺层状, 厚度约 30 m 3.60 m
11. 灰紫色中层含砾粗砂岩夹灰色粗砂岩, 后者多呈透镜状 1.40 m
10. 砖红色厚层泥质粉砂岩—细砂岩, 含钙质结核 28.60 m
9. 灰白色、浅灰绿色薄层细砂岩与紫红色粉砂质泥岩互层, 含钙质结核 8.00 m
8. 灰色、灰紫色粉砂岩 39.70 m
7. 灰白色、浅灰色粗砂岩, 底部含砾石 1.10 m
6. 灰色、浅灰紫色含砾中粗粒砂岩夹砖红色中细粒砂岩 0.80 m
5. 紫红色含砾粗砂岩, 砾石以安山岩为主, 次圆状—圆状 1.10 m
4. 灰色砾质粗砂岩夹砖红色中薄层中细粒砂岩 0.50 m
3. 灰色薄层砾岩夹浅灰紫色中薄层含砾粗砂岩 0.80 m
2. 灰色、灰紫色粉砂岩 2.10 m
1. 灰色砾岩, 砾石以白云岩为主, 不整合于髻山组集块角砾岩之上 0.10 m
- 平行不整合-----
0. 髻髻山组: 紫红色安山质集块角砾岩 >10 m

## 2.2 沉积相

### 2.2.1 滨浅湖

主要发育于土城子组的一段和三段, 沉积物粒度较细, 根据不同的沉积物组合韵律特征, 可细分为滨湖相(LK)和浅湖相(SLK)沉积(图 2)。其中, 滨湖相由灰色、灰紫色含砾粗砂岩、粗砂岩夹细砂岩组成, 砾石磨圆度较好, 多呈次圆状, 大小一般 5~10 cm, 发育水平层理(图 3-a), 可见泥裂等间歇暴露标志和生物潜穴、钙质结核等沉积构造现象(图 3-b), 表明当时炎热干燥的气候特征; 浅湖相则由紫红色、灰绿色粉细砂岩、泥质粉砂岩组成, 局部可见植物化石碎屑, 部分地段含不稳定的薄煤层, 水平层理发育, 垂向上构成向上逐渐变细的沉积层序。此外, 整个层序上表现出滨湖—浅湖交替出现的特征, 推测当时受火山构造活动影响, 湖水较动荡。

### 2.2.2 辫状河

多见于土城子组二段中下部和四段, 沉积物粒度较粗, 以含砾粗砂岩、粗砂岩为主。根据沉积物岩性

组合特征, 划分为河道沉积(RB)和泛滥平原沉积(FP)(图 2)。前者可进一步细分为心滩沉积和河道滞留沉积, 其中心滩沉积粒度一般较粗, 以中粗砂岩为主, 下部发育大型槽状交错层理、板状交错层理, 向上粒度逐渐变细, 出现厚度不大的薄层细砂岩(图 3-c)。河道滞留沉积位于辫状河沉积体系的最下部, 底界与下伏地层之间常存在一个明显的侵蚀面(图 3-d), 垂向上延伸不稳定。沉积物粒度粗, 主要由砂砾岩、含砾砂岩组成, 偶见“泥砾”。砾石多呈较明显的叠瓦状构造(图 3-e), 含砂岩透镜体; 泛滥平原位于辫状河沉积体系上部, 沉积物粒度较细, 类型简单, 一般由细砂岩、粉砂岩和泥质粉砂岩组成向上变细的序列(图 2)。多发育水平层理, 局部可见到有厚度不大的根土岩层, 其中可见少量植物和虫孔, 显示了典型的陆上河流平原沉积特征。

### 2.2.3 曲流河

发育于土城子组二段中上部和四段下部, 位于辫状河沉积体系的上部, 沉积物粒度明显变细, 具有典型的“河流二元结构”, 沉积物由含砾砂岩、粗砂岩、细砂岩和粉砂岩组成。按不同岩性组合分为河道沉积(RB)和河漫滩沉积(FP), 其中河道沉积位于曲流河沉积的下部, 发育河道滞留沉积和边滩沉积, 前者沉积物粒度较粗, 主要由浅灰绿色含砾粗砂岩组成, 局部可见泥砾, 发育平行层理和小型交错层理, 与下部的细砂岩之间见明显的侵蚀面; 边滩沉积位于河流滞留沉积的上部, 岩性主体为细砂岩、粉细砂岩, 发育小型交错层理和爬升波痕层理。泛滥平原位于曲流河沉积的上部, 沉积物粒度以紫红色、灰绿色细砂岩、粉细砂岩为主, 发育水平层理。此外, 河漫滩顶部层面可见大量的波痕、泥裂、雨痕等沉积构造标志(图 3-f), 以及恐龙足迹和近原地倒伏的河北松型球果 *Pityostrobus hebeiensis* Wang(sp.nov.) 等木化石(图 3-g), 总体代表了浅水甚至间歇性暴露的沉积环境特征。

### 2.2.4 洪积扇

多见于土城子组二段的上部和四段, 沉积物粒度较粗, 岩性以灰紫色砾岩、砂砾岩为主, 砾石成分以白云岩为主夹少量粗砂岩, 含少量变质岩、火山岩, 层理不明显, 多以巨厚层、块层状产出, 砾石分选和磨圆均较差(图 3-h), 底部常发育侵蚀冲刷面, 并与相邻地层序列呈沉积环境的突变。

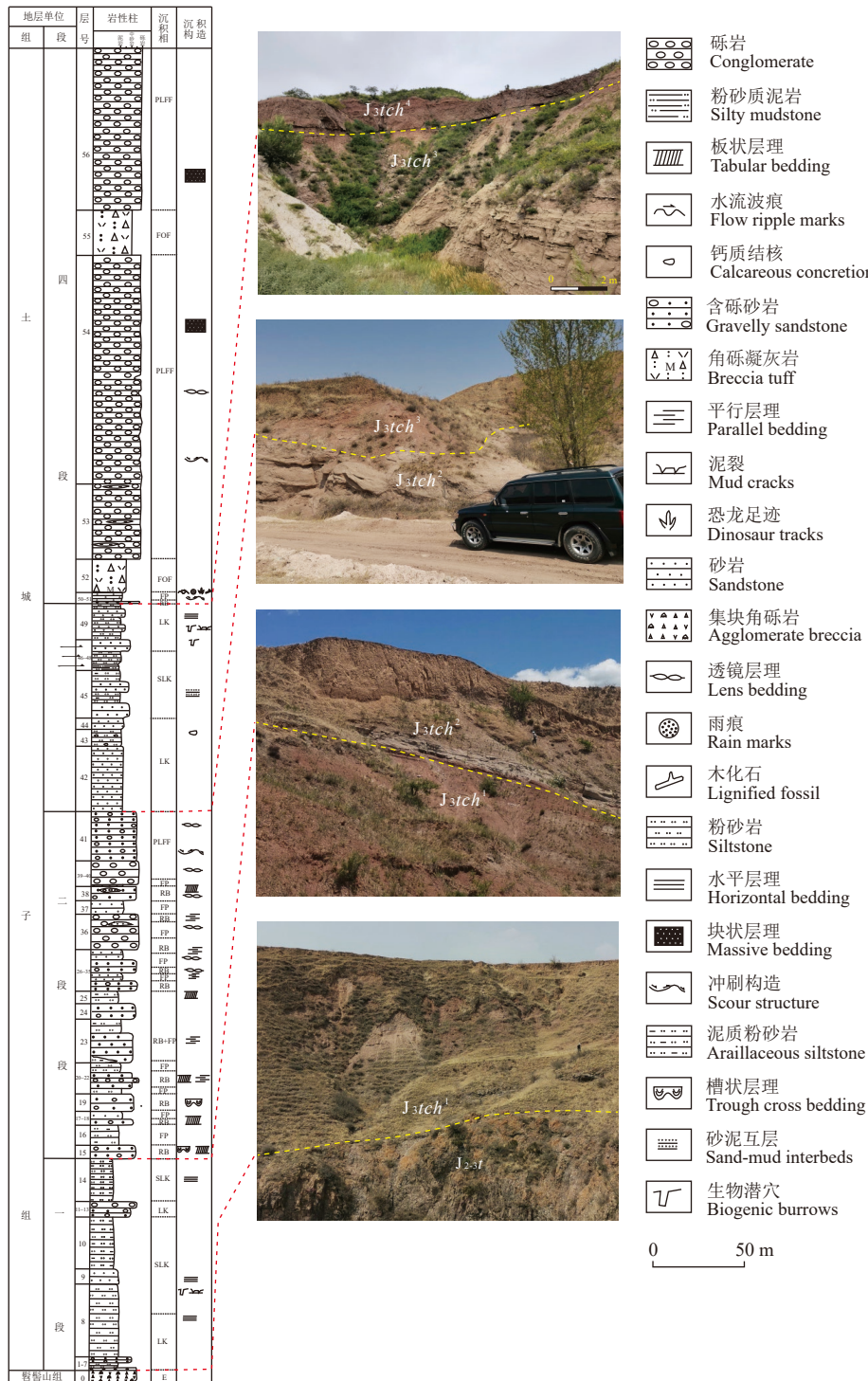


图 2 宣化立石土城子组剖面沉积序列图

Fig. 2 Sedimentary sequence diagram of the Tuchengzi Formation from Lishi section in Xuanhua

LK—滨湖相; SLK—浅湖相; RB—河道相; FP—泛滥平原相; PLFF—洪积扇相; FOF—火山空落相; E—火山爆发相;

$J_3tch^1$ —土城子组一段;  $J_3tch^2$ —土城子组二段;  $J_3tch^3$ —土城子组三段;  $J_3tch^4$ —土城子组四段

LK—Lakeside facies; SLK—Shallow lacustrine facies; RB—River channel facies; FP—Floodplain facies; PLFF—Alluvial fan facies; FOF—Volcanic void facies; E—Volcanic eruption facies;  $J_3tch^1$ —The first Member of the Tuchengzi Formation;  $J_3tch^2$ —The second Member of the Tuchengzi Formation;  $J_3tch^3$ —The third Member of the Tuchengzi Formation;  $J_3tch^4$ —The fourth Member of the Tuchengzi Formation

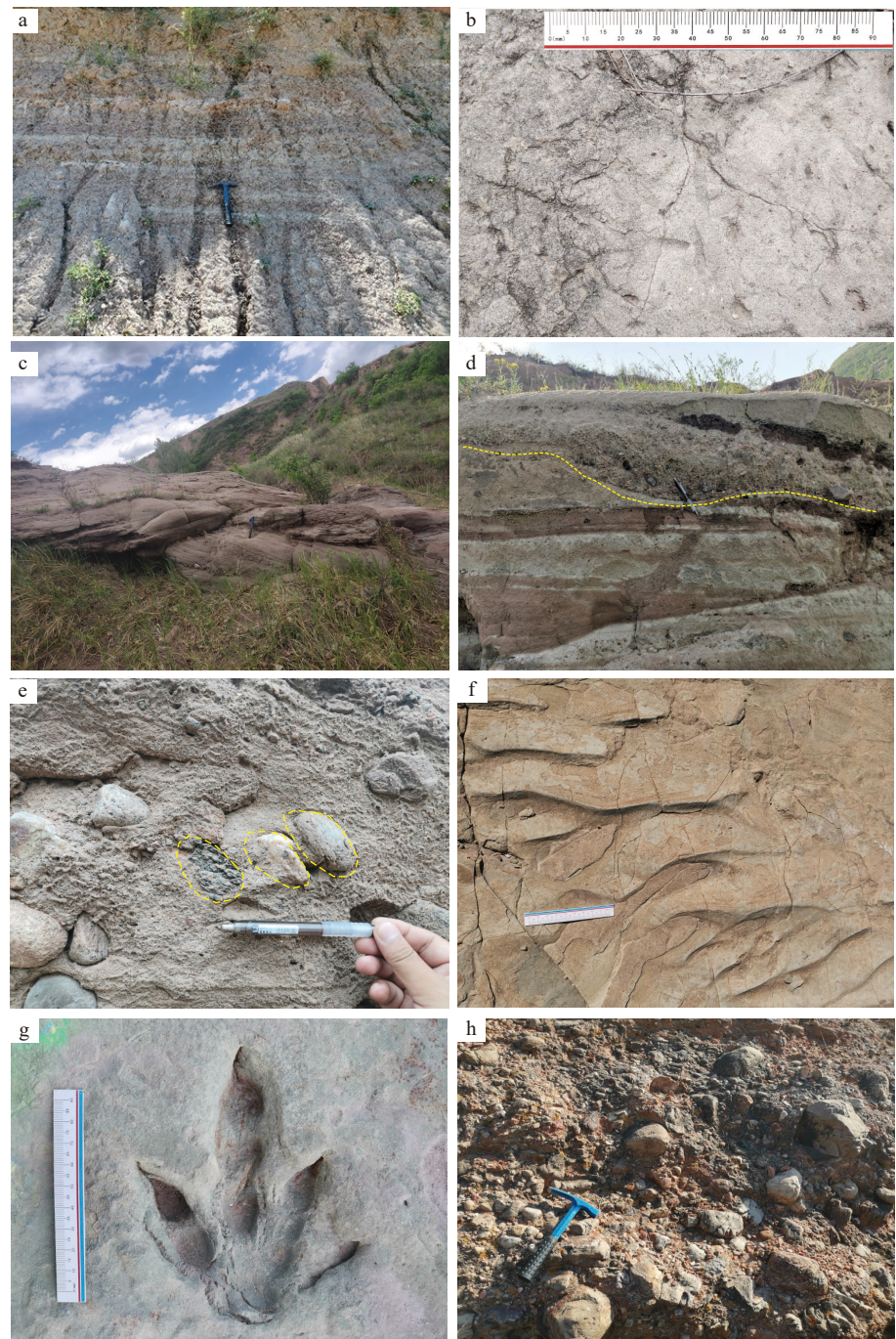


图3 宣化立石村土城子组地层接触关系、沉积构造现象及层面暴露现象

Fig. 3 Photographs of strata contact relationship, sedimentary structures and layer exposure of the Tuchengzi Formation from Lishi section in Xuanhua

- a—水平层理; b—虫迹; c—交错层理; d—冲刷面; e—叠瓦状构造; f—波痕; g—恐龙足迹; h—砾岩  
a—Horizontal bedding; b—Pest ichnology; c—Cross bedding; d—Erosional basal surface; e—Imbricate structure;  
f—Wavy print; g—Dinosaur footprints; h—Conglomerate

3 分析与讨论

研究区立石村土城子组剖面按不同岩性组合特

征,可划分为4个段级单位(图3)。其中,一段下部由粉砂岩夹薄层含砾砂岩的多个沉积小旋回组成,代表了滨湖沉积环境的产物。上部由紫红色泥质粉

砂岩、薄层细砂岩,局部夹透镜状含砾砂岩构成基本层序,显示了浅湖沉积环境;二段下部为含砾粗砂岩夹砾岩,发育大型交错层理,代表辫状河沉积。中部由厚度不大的粗砂岩、细砂岩夹泥质粉砂岩组成向上变细的沉积序列,构成典型的“河流二元结构”。上部由厚层砾岩夹含砾粗砂岩构成,是辫状河沉积的产物;三段底部为灰绿色细砂岩,向上过渡为紫红色粉砂岩、泥质粉砂岩、灰绿色砂岩夹中砂岩,发育水平层理,可见泥裂、生物潜穴等沉积构造,为一套滨湖相和浅湖相沉积;四段沉积物粒度总体较粗,下部发育河流相沉积砂岩、粉砂岩,为恐龙足迹化石的赋存位置。尤其是四段中上部以灰紫色砾岩、砂砾岩为主,砾石成分以白云岩为主夹少量粗砂岩,含少量变质岩、火山岩,层理不明显,多以巨厚层、块层状产出,砾石分选性和磨圆度均较差,代表快速堆积山前冲洪积扇沉积,并夹 2 层厚度 20~30 m 的流纹质熔接角砾凝灰岩,自下而上依次为第 1 层、第 2 层,前人先后自第 1 层中获得系列定年结果。朱本鸿等(2020)获得锆石 U-Pb 年龄为  $142.21 \pm 0.86$  Ma; Xing et al.(2021)在恐龙足迹之下 90 m 的凝灰岩中获得了 U-Pb 年龄为  $142.2 \pm 0.9$  Ma; 鞠书彬等(2022)获得锆石 U-Pb 年龄为  $152.3 \pm 0.3$  Ma; 负杰等(2022a)获得锆石 U-Pb 年龄为  $153.0 \pm 3.0$  Ma。

燕辽地区土城子组在每个盆地的地层层序、充填沉积序列和岩石组合都存在差异,因此对其岩性段的划分也不统一。孙立新等(2007)根据其沉积充填特征划分为粗—细—粗和细—粗 2 种模式,第一类以尚义—土木路、承德盆地为代表,该模式下部岩性为砾岩、凝灰质砾岩及含砾粗砂岩夹少量粉砂岩、粉砂质页岩;中部为砂岩、粉砂岩夹少量含砾粗砂岩、凝灰岩;上部为厚层状砾岩、砂岩。第二类以密云新城子盆地、寿王坟—大杖子盆地土城子组为代表,其下部为粉砂岩、粉砂质泥岩夹少量含砾粗砂岩,上部过渡为砂岩、含砾砂岩和砾岩。本文宣化立石土城子组地层层序和沉积序列大体属于第二类,但该地区土城子组中上部发育一套湖相细碎屑沉积,本次研究将其单独划分为 3 段,向上则逐渐演变为短暂河流相河漫滩沉积的细砂岩和粉砂岩,而其上被迅速降落的凝灰岩(测年样品和数据层位)覆盖,再向上为厚层、巨厚层的洪积砾岩充填(图 4)。尽管土城子组的区域性划分对比存在不同方案(贾建称, 2003; 李忠等, 2003; 柳永清等, 2003; 孙立新, 2007;

张宏, 2008; 许欢等, 2011, 2014; Xu et al., 2012; 王思恩, 2013),但实际上,从前人报道的燕山地区土城子组层序、沉积序列和该组内恐龙等足迹发育层位的区域对比可见(郑少林, 2000; 柳永清等, 2002, 2003, 2012; 贾建称等, 2003; 邵济安等, 2003; 翟明国等, 2003; 刘少峰等, 2004; 王五力等, 2004; 张永忠等, 2004; Davis, 2005; 季强等, 2006; 渠洪杰等, 2006; 孙立新等, 2007; 和政军等, 2008; 张宏等, 2008; Sullivan et al., 2009; 柯舒文等, 2009; 许欢等, 2011, 2013, 2014, 2016; 王思恩, 2013; 章朋等, 2014; Xing et al., 2015, 2020, 2021a, b; 刘晓波等, 2016; Xu et al., 2018; 万晓樵等, 2020; 贺瑾瑞等, 2021; 李晓波等, 2021),冀北—辽西地区土城子组内发育的恐龙等足迹可以出现在土城子组的不同位置,但大多出现在该组顶部。

如图 3 所示,冀北承德和围场恐龙足迹产出层位赋存于土城子下部和顶部,而辽西朝阳和北票恐龙足迹出于当地土城子下部和顶部,本次研究显示,宣化恐龙足迹应发育在土城子组中上部,但不是产于土城子组下部(鞠书彬等, 2022)。实际上,相邻的张家口尚义盆地恐龙足迹也是位于土城子组上部。然而,以往对土城子组恐龙等足迹的研究也似乎都指示它们大多发育在土城子组顶部三段(Yabe et al., 1940; 张永忠等, 2004; Lockley et al., 2006; Sullivan et al., 2009; Xing et al., 2009, 2012; 柳永清等, 2012; 张建平等, 2012)。但由于前述土城子组的区域性划分对比存在不同方案,目前无法判断土城子组内恐龙足迹产出层位在区域上是否可对比,或产于一致或不一致的层位。

前人对区域上和本次研究的土城子组及其中所赋存的恐龙足迹也进行过大量的定年研究,并认为土城子组底、顶位于 154~153 Ma 和 137~136 Ma 期间(杨进辉等, 2006; 张宏等, 2008)。同时,辽西朝阳、北票、承德等地恐龙及鸟类等足迹层都较可靠地年轻于 147 Ma,最年轻为 139~137 Ma(图 4);但张家口地区赤城的恐龙足迹年轻于 157 Ma。对于研究区,前人获得恐龙足迹层直接上覆凝灰岩的锆石 U-Pb 年龄分别为 155 Ma(Xing et al., 2021)、152.3 Ma(鞠书彬等, 2022)、153.0 Ma(负杰等, 2022a)。然而,朱本鸿等(2020)对研究区恐龙足迹上覆凝灰岩定年获得 142.2 Ma 的数据,并据此将其归属于早白垩世张家口组下部。因此,依据目前研究区报道的恐龙足迹上覆凝灰岩测年数据推测,宣化恐龙足迹

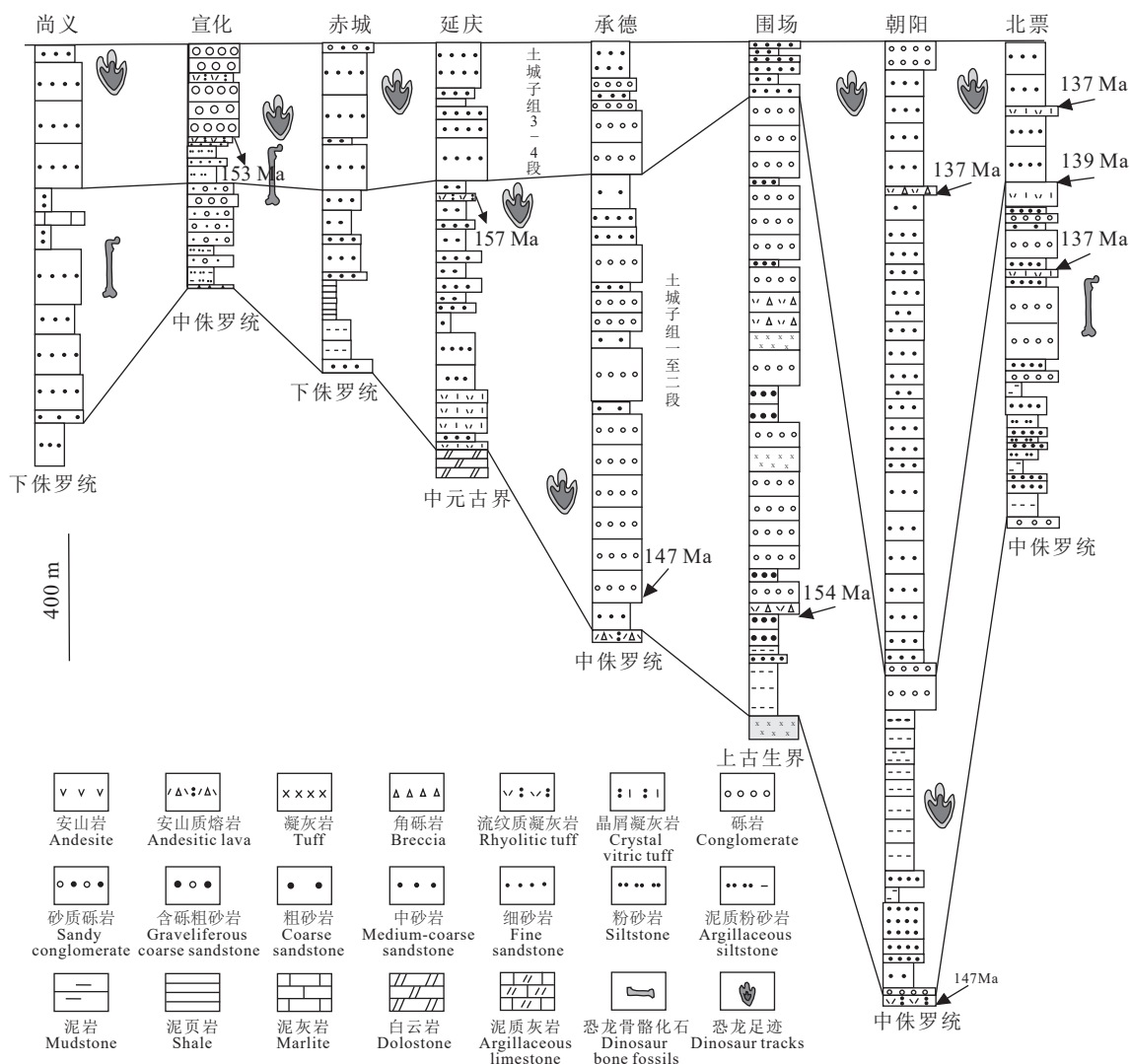


图4 燕辽地区土城子组岩石地层—年代学格架与恐龙足迹层位对比(据柳永清等,2012 修改)

Fig. 4 Stratigraphic columnar section of the Tuchengzi Formation from dinosaur footprint layer correlation of lithostratigraphic and chronological framework of dinosaur footprints and bone fossils of the Upper Jurassic—Lower Cretaceous Tuchengzi Formation in Yanliao area

的发育不早于晚侏罗世早期,北京延庆千家店盆地土城子组恐龙足迹可能也形成于该时期(贺瑾瑞等,2017),也可能发育于早白垩世早期,这与前人报道的区域上恐龙、鸟类等足迹时代区间吻合,但仍不能确定本次研究的恐龙足迹是否与区域上冀北、辽西等地的土城子组恐龙等动植物群的时代一致。

#### 4 结 论

(1)河北宣化地区土城子组按照岩性组合特征可划分为4段,恐龙足迹化石赋存于四段下部的细砂岩、粉砂岩之上,即整个土城子组层序中上部,并非是人认为的该组底部。

(2)研究区土城子组自下而上由2个滨浅湖—辫状河(间夹曲流河)—洪积扇沉积旋回序列构成,恐龙足迹埋藏于河流相河漫滩沉积相(沉积物表面)。

(3)宣化土城子组恐龙足迹上覆凝灰岩多组定年数据指示,其形成时代为155~142 Ma(晚侏罗世晚期—早白垩世早期)。

(4)根据上覆凝灰岩测年数据推测,宣化恐龙足迹可能形成于晚侏罗世早期—早白垩世早期。

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