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辽宁兴城中元古界常州沟组砂岩中微生物成因沉积构造

李晓波^{1,2}, 王旖旎¹, 王晗¹

1. 吉林大学地球科学学院, 长春 130061

2. 多伦多大学密西沙加校区生物学系, 安大略省 L5L 1C6

摘要 辽宁兴城夹山中元古界常州沟组潮间带相砂岩层面产出裂隙状构造。这些构造由0.8~3 cm长的纺锤状短裂隙和超过7 cm的长延伸裂隙组成, 孤立为主, 部分相连。通过与类似的层面裂隙和现代微生物席干缩裂隙的比较分析, 将其解释为微生物成因沉积构造分类体系中的收缩裂隙(Shrinkage crack), 并参考席裂多边形(Mat-crack polygon)的术语称其为席裂(Mat-crack)。微生物席在脱水不充分的情况下形成纺锤状席裂, 脱水充分的情况下形成席裂多边形。这些构造在常州沟组的出现, 表明微生物生态系统在华北克拉通中元古代海侵初期已经开始影响古海岸带的地质作用, 这对于恢复燕山裂陷槽盆地的生物—沉积作用和环境演化具有重要意义。

关键词 微生物席; 古环境; 潮间带; 前寒武纪; 长城系

第一作者简介 李晓波, 男, 1982年出生, 讲师, 古生物演化、古环境、古地理, E-mail: lixiaobo@jlu.edu.cn

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0 引言

二十多年来, 砂岩沉积中的微生物成因沉积构造(Microbially Induced Sedimentary Structures, 简称MISS)被识别和深入研究^[1-13], 引起了沉积学和古生物学领域的一场“革命”^[6]。越来越多的微生物成因沉积构造在前寒武纪滨浅海相砂岩和泥岩中被发现^[14-16], 为了解早期地球环境的演化, 尤其是地质—微生物系统的交互作用提供了新的材料^[17-19]。太古宙至古元古代是华北克拉通早期地壳演化和结晶基底形成阶段^[20-22], 随着哥伦比亚超大陆自中元古代早期广泛裂解^[21, 23], 华北克拉通上也开始出现大陆裂谷盆地。位于现今河北北部和辽西地区的中、新元古代盆地被称为燕山裂陷槽^[24], 盆地沉降中心(天津蓟县)沉积的中、新元古界不仅是全球地层对比的标准剖面之一^[25], 地层中的微体和宏体藻类化石^[26-29]、叠层石^[30]、沉积建造^[31]、以及同位素地球化学记录^[32-33]等更是为了解前寒武纪地球环境演化提供了关键数据。

前寒武纪砂岩中MISS构造也引起了国内学者的密切关注^[34-36], 在华北长城系串岭沟组、大红峪组、以及蓟县系碳酸盐岩地层中发现了大量MISS构造^[37-45]。常州沟组是燕山裂陷槽盆地发育最早期形成的一套滨海—浅海相陆源碎屑岩组合, 文献中有提到产出微体化石^[28]、形似宏观藻类的泥质斑点/假化石^[46]、以及疑似的后生动物潜穴^[47]。于晓辉等^[48]报道了在辽宁兴城常州沟组砂岩薄片内观察到的微生物席碎片结构, 与本文所研究的是同一剖面, 层位相近。本文描述及讨论产自兴城夹山西剖面常州沟组的一些宏观的层面裂隙状构造, 将其与多种类似构造进行了对比分析, 认为其属于微生物成因沉积构造分类体系中的收缩裂隙(Shrinkage crack), 参考席裂多边形(Mat-crack polygon)的术语称其为席裂(Mat-crack), 并初步讨论了席裂构造的古环境意义。

1 地质背景和地层特征

1.1 区域地质背景

研究区位于中国东北辽西南部, 辽宁省葫芦岛

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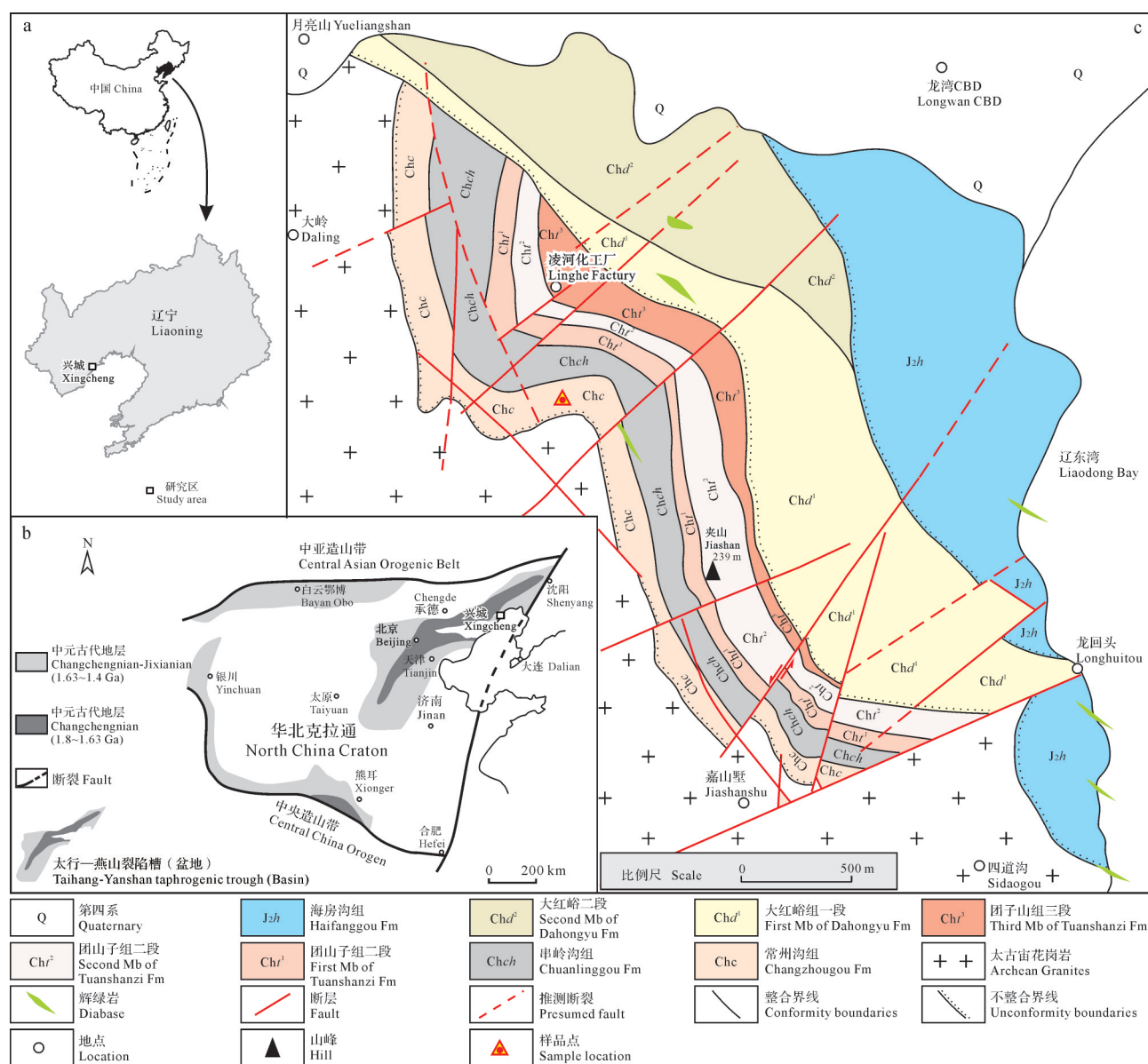


图1 研究区地理位置与地质简图(图b据 Zhao *et al.*^[20]修改,图c为实测编制)

Fig.1 (a) Geographic location of study area; (b) sketched geological map of the study area (modified from Zhao *et al.*^[20]);

(c) geological map by the authors

市兴城地区(图1)。研究区大地构造位置位于华北克拉通中、新元古代燕山裂陷槽盆地的东部(图1b);区内大面积分布的新太古代花岗岩是构成山海关古陆(古隆起)的主体,时代大约为2.5 Ga^[49];前寒武纪至晚古生代发育典型的华北地台型地层序列^[50-54];中生代受印支运动和燕山运动的强烈影响,发育火山—沉积盆地^[55-56];新生代相对隆起为辽西山地,成为渤海盆地沉降充填的物源区之一。

辽西南部中、新元古界的特征总体可与蓟县剖面对比^[50,57-60],经 1:25 万区调工作的修订^[60],自下而上

划分为:长城系(常州沟组、串岭沟组、团山子组、大红峪组)(图2),蓟县系(高于庄组、杨庄组、雾迷山组),青白口系(长龙山组、景儿峪组)。但是本区地层的特殊性也很明显,比如:厚度总体较小,长城系碳酸盐岩发育很少,陆源碎屑沉积粒度较粗,蓟县系铁岭组、洪水庄组、待建系下马岭组缺失,几大沉积层序的底界超覆明显。上述特征是典型的盆地边缘沉积特点。

研究区长城系主要分布在兴城和葫芦岛沿海丘陵,蓟县系和青白口系主要分布在八家子、杨家杖

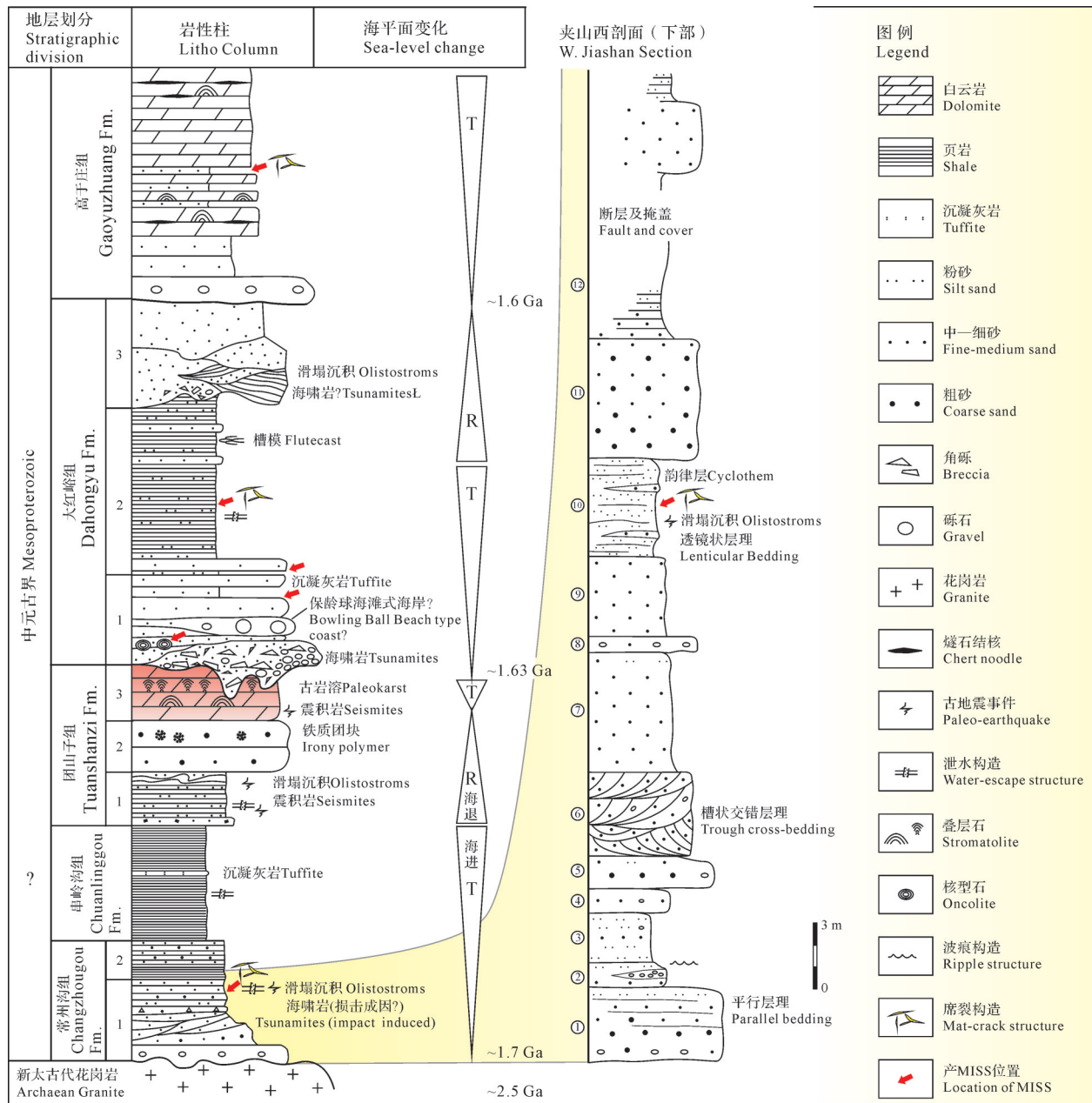


图2 兴城地区长城系与夹山西剖面常州沟组沉积序列柱状图(左侧长城系整体的序列据夹山、首山、茶棚庵、磨盘山、望海寺等剖面综合而成)

Fig.2 The columns of the Changchengian System in Xingcheng area and the sedimentary sequence of Changzhoukou Formation in West Jiashan Section. Left: Sequences of Changchengian System compiled from Jiashan, Shoushan, Chapengan, Mopanshan and Wanghaisi sections

子、钢屯以及娘娘庙等区域^[50,57,60]。中元古界常州沟组至团山子组为一套局限分布的滨浅海相海进至海退旋回沉积^[51-52,61-62]；大红峪组以石英砂岩和粉砂质页岩为主，下部发育复成分角砾岩和单成分砾岩^[52,63]，与下伏地质体有不整合(沉积接触)、角度不整合、微角度不整合、岩溶不整合等多种接触关系^[52,54,63-66]。这些不整合形成的古地理背景是大红峪

组沉积之前发生过局部的盆地内部或边界断裂活动，导致早期地层发生倾斜和褶皱(图1c)，之后经历不长时间的风化剥蚀，形成复杂的古地形和基岩分布；蓟县系高于庄组在兴城北部磨盘山一小盖州地区出露，为一套海侵序列，底部石英砂岩质砾岩微角度超覆不整合在大红峪组之上。前人曾将其作为大红峪组与常州组之间的不整合^[64]，或者认为属于扇三

角洲沉积^[65],对地层修订后认为属于高于庄组与大红峪组之间的超覆不整合^[60]。由于特殊的古地理位置,兴城地区前寒武纪地层中记录了丰富的生物、事件沉积现象^[52,54,66-67](图2),对于探讨古陆边缘沉积古地理有重要意义。

1.2 常州沟组地层特征

兴城地区的常州沟组是一套滨—浅海相陆源碎屑岩,沉积覆盖在新太古代花岗岩之上,剖面出露于兴城北部的首山、夹山、以及葫芦岛望海寺海滨^[50,58]。1:20万区域地质图中兴城市铁马山、磨盘山、地藏寺等地区表示的常州沟组经1:25万区调工作修订为大红峪组的下段^[50,60]。常州沟组在兴城北东约10 km的夹山区域出露最好最全(图1),下段岩性(图2)如下:最底部为磨圆及分选均不好的含砾长石粗砂岩,局部富集磨圆中等的石英岩质中、粗砾岩,底砾岩之上为含砾长石砂岩,含有一些暗色的风化残余铁锰质碎屑物。向上为紫灰色中厚层具槽状交错层理的中、细粒砂岩,再逐渐变为灰黑色中、薄层和纹层状粉砂岩、细砂岩、中粒砂岩、粗砂岩等组成的韵律沉积。粉砂岩层面见有裂隙状构造,本文解释为微生物席收缩脱水相关的席裂构造(Mat-crack)(图2~4)。上述岩石组合主体为紫红色调,碎屑物自下而上由粗到细、岩层由厚变薄,发育小—中型槽状交错层理、丘状交错层理、冲洗层理以及浪成波痕等沉积构造,指示干旱气候下的滨海相环境;上段岩性为:紫灰色、灰色中厚层中粗粒长石石英砂岩,向上砂岩粒度变细、厚度变薄,逐渐向上覆串岭沟组粉砂质页岩渐变,体现海进演化过程(图2)。国际地层表和中国区域地层表对于古/中元古代界线年龄有1.6 Ga和1.8 Ga的长期争议,本文暂以中国地学界传统认识将常州沟组时代表示为中元古代,不讨论更多时代问题。

2 常州沟组席裂构造特征

本文描述的席裂构造来自三个层面,但属于同一分层(第10层)(图2),野外可见明显的裂隙状构造分布在灰黑色粉砂岩薄层表面(上层面)(图3,4),裂隙内部充填浅肉红色细—中粒砂质颗粒。裂隙大部分为弯曲状,长度主要0.8 cm至3 cm不等,个别可超过7 cm(图3a),延伸方向和形状不规则。砂质颗粒充填向上突起0.1 m至0.3 cm(图5)。裂隙边缘的灰黑色粉砂质层卷曲变形普遍,部分在裂隙边缘

发生褶皱(图3c)。短裂隙常呈纺锤状(图3d),大部分孤立,部分有交割或连接关系(图3c),未见到多组裂隙交割围限的多边形构造—席裂多边形(Mat-crack polygon)。

于晓辉等^[48]描述了辽宁兴城常州沟组下部粗碎屑砂岩薄片内观察到的微生物砂质颗粒结构,其论文中表示出的层位相当于图2所列剖面的第⑥层,薄片中的MISS构造为沿着粗碎屑砂岩交错层理分布的磨圆状微小颗粒^[48]。本研究未在第⑥层发现宏观的微生物席相关沉积构造,而在之上的第⑩层波状层理、透镜状层理砂岩中发现大量的席裂构造。

3 常州沟组席裂构造的成因及其与类似构造的比较

本文分析这些构造与微生物席相关主要是基于宏观特征,虽然目前还缺少进一步的微观数据,但由于该层位之下可能存在MISS构造^[48],说明微生物生态系统已经在该沉积区域形成。通过对多种沉积岩中裂隙状构造的对比,本文认为上述裂隙构造与微生物席的收缩张裂有关。根据形态特征,这些席裂构造与天津蓟县剖面串岭沟组页岩内发育的“纺锤状裂隙”最为相似(图4e),只是后者延伸平直,弯曲较少。通过与现代微生物席中的脱水裂隙对照(图4b,d,f),两者的轮廓和尺寸也非常接近,但后者尚未有碎屑物在裂隙内充填。在陆源碎屑岩中微生物席被发现和大量研究以前,这种类似裂隙构造常常被描述为“泥裂”或者“泥裂状构造”^[25,68],或者解释为古地震引起的层面裂隙^[69],甚至有时候被误认为后生动物的遗迹化石^[70]。串岭沟组的裂隙构造和本文的材料不仅地层时代与后生动物的起源和演化序列有巨大差异^[71],形态也有明显区别。席裂构造内充填的砂质颗粒一般来自微生物席之下,在层面上突起(图3、图4a、图5c,d),而遗迹化石中的类似结构因为一般是潜穴铸模而在下层面下突出。史晓颖等^[72],汤冬杰等^[73]对天津蓟县串岭沟组的纺锤状裂隙构造进行了详细研究,认为与微生物席的破裂有关,将其解释为甲烷气体逃逸成因。

关于天津蓟县剖面串岭沟组纺锤状裂隙构造的成因曾长期争论,最近的焦点是其为古地震还是微生物席相关成因^[68-69,72-73]。在同沉积古地震的作用下,一些泄水砂脉也会从细碎屑层下方上突,但这种

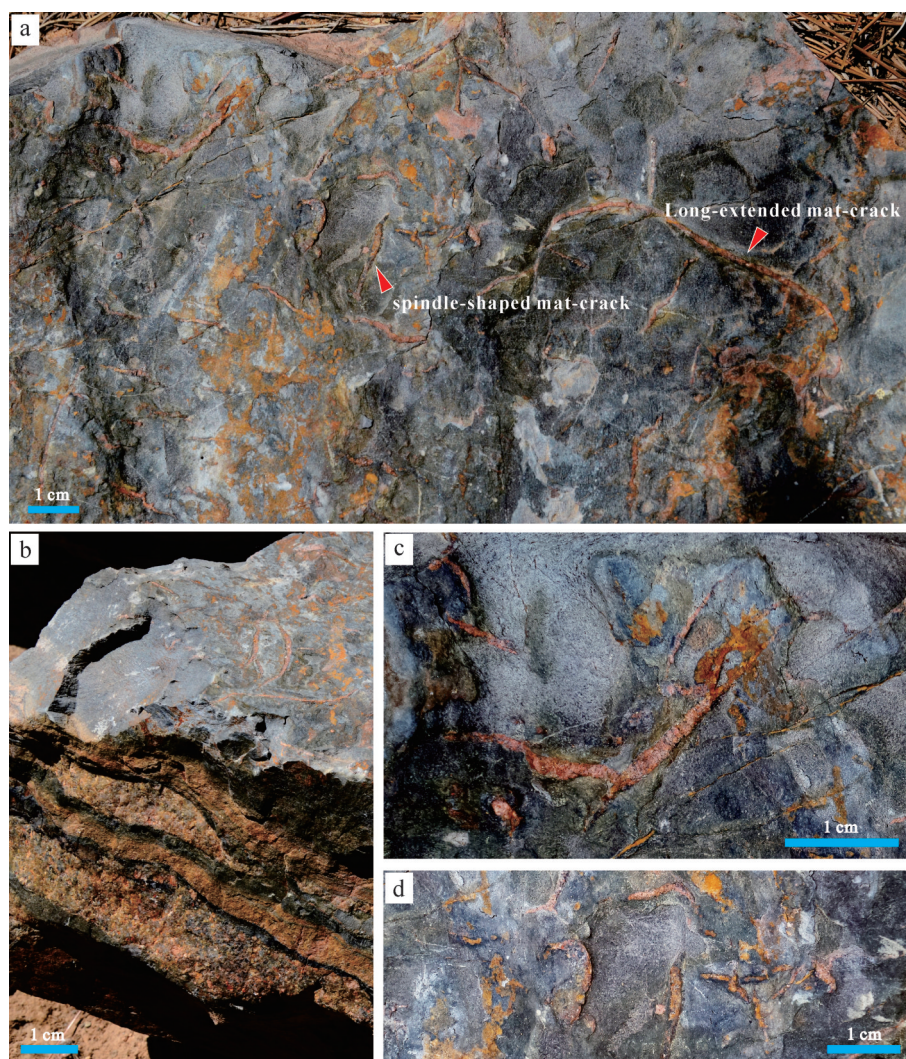


图3 兴城夹山西剖面常州沟组砂岩层面上的席裂构造

(a)砂岩层面席裂构造宏观视域;(b)具席裂构造砂岩侧面,粗粒砂岩与灰黑色泥质、粉砂质纹层互层,具透镜状层理;(c)纺锤状的席裂构造;(d)纺锤状的席裂构造,相互间孤立或者交割现象均存在

Fig.3 Microbial mat crack structures on the sandstone surface of the Changzhougou Formation in West Jiashan Section, Xingcheng

(a) macro view of mat-cracks on the sandstone surface; (b) edge-on view of the sandstone bearing mat-cracks; (c) spindle-shaped mat-cracks; (d) both isolated and connected spindle-shaped mat-cracks

情况下沉积层表面的裂隙会交割围限成复杂且不规则的多边形网络,裂隙边缘不均匀锯齿状,岩层侧面可见到震裂结构^[74]。串岭沟组的材料从其层面特征和样品镜下切面来看,裂隙发生的层面确定存在微生物席,侧面可见类似白齿状构造的砂脉(Sand vein)^[68-69,72-73]。关于碳酸盐岩中白齿状构造的成因有一种甲烷气体逃逸引起碳酸钙质沉淀的解释^[75],而古地震产生的砂脉一般不伴随钙质沉淀的过程^[74]。仅从形态而论,地震液化砂脉和白齿状构造有时是难以区分的^[74,76]。串岭沟组砂脉的成因虽然解释为甲

烷气体逃逸引起^[72-73]比较合理,但并不能排除古地震事件对这一机制的诱发^[68-69]。兴城地区大红峪组中部粉砂质页岩与砂岩薄层互层岩性中也产出席裂构造(图5e, h),显微镜下能见到确切的微生物席残余碎屑纹层(图5f),岩层侧面见有大量类似白齿状构造的砂脉(图5g),这样的现象与天津蓟县串岭沟组“纺锤状裂隙”(席裂)层位非常类似^[69]。因此,微生物席和泄水砂脉的共同产出并不冲突。

本文描述的常州沟组席裂内的充填物砂质颗粒(图3、图4c, d),砂脉下部宽,顶部圆滑收窄(图5c,

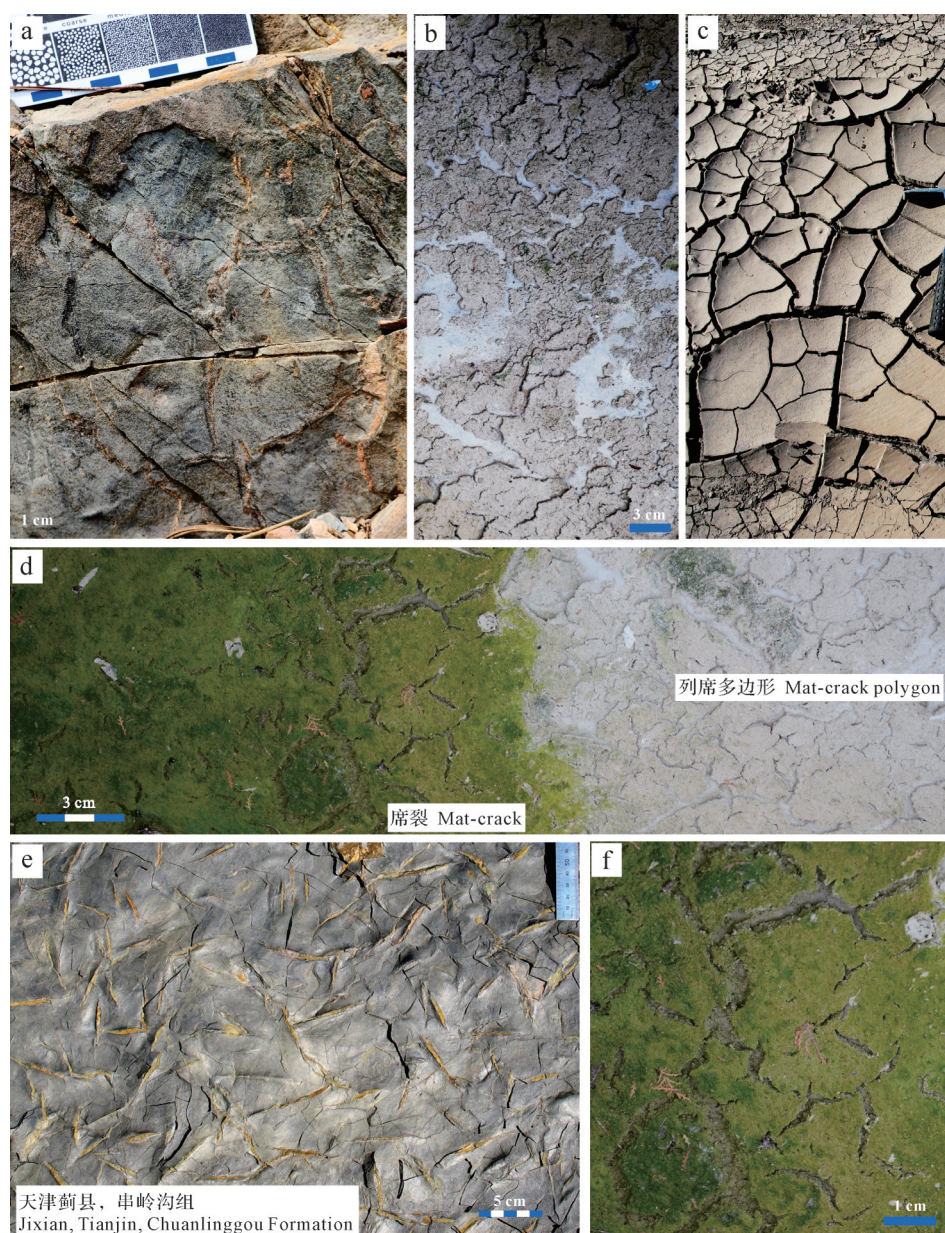


图4 常州沟组裂隙状 MISS 构造与类似构造的对比

(a)常州沟组席裂构造;(b)现代席裂构造;(c)现代泥裂构造;(d)现代席裂构造,程度不一致的脱水席裂;(e)天津蓟县串岭沟组席裂构造/纺锤状裂隙;(f)现代席裂构造

Fig.4 Comparison between mat-cracks in the Changzhougou Formation and similar structures

(a) mat-cracks from the Changzhougou Formation; (b) mat-cracks in modern setting; (c) mud-cracks in modern setting; (d) mat-cracks in modern setting, showing uneven shrinkage; (e) mat-cracks from the Chuanlinggou Formation in Jixian, Tianjin; (f) mat-cracks in modern setting

d),说明是由下向上充填。含微生物席层面之上覆盖的岩层仍然是灰黑色粉砂质沉积物为主,也说明砂质流体不是来自上覆岩层。部分区域砂质颗粒横向分布呈片状(图5d),说明砂质颗粒也曾沿着层理界面运移(图6u)。在剖面上该段地层还可见到同沉积生长小断层和包卷构造等现象(图5b),所以有可能古地震诱发的同沉积变形引起微生物席之下的砂

质流体向席裂流动及充填,但变形时微生物席之上是否已有沉积物覆盖尚难以确定。部分纺锤状席裂发生比较强烈的弯曲变形(图3),可能也与同沉积变形有关,因为纺锤状席裂本身代表脱水程度较弱,仅干缩过程难以造成这样程度的变形。常州沟组席裂构造的成因是微生物席脱水产生裂隙,之后发生砂脉上涌及顺层运移将其充填(图6u)。另外,常州沟

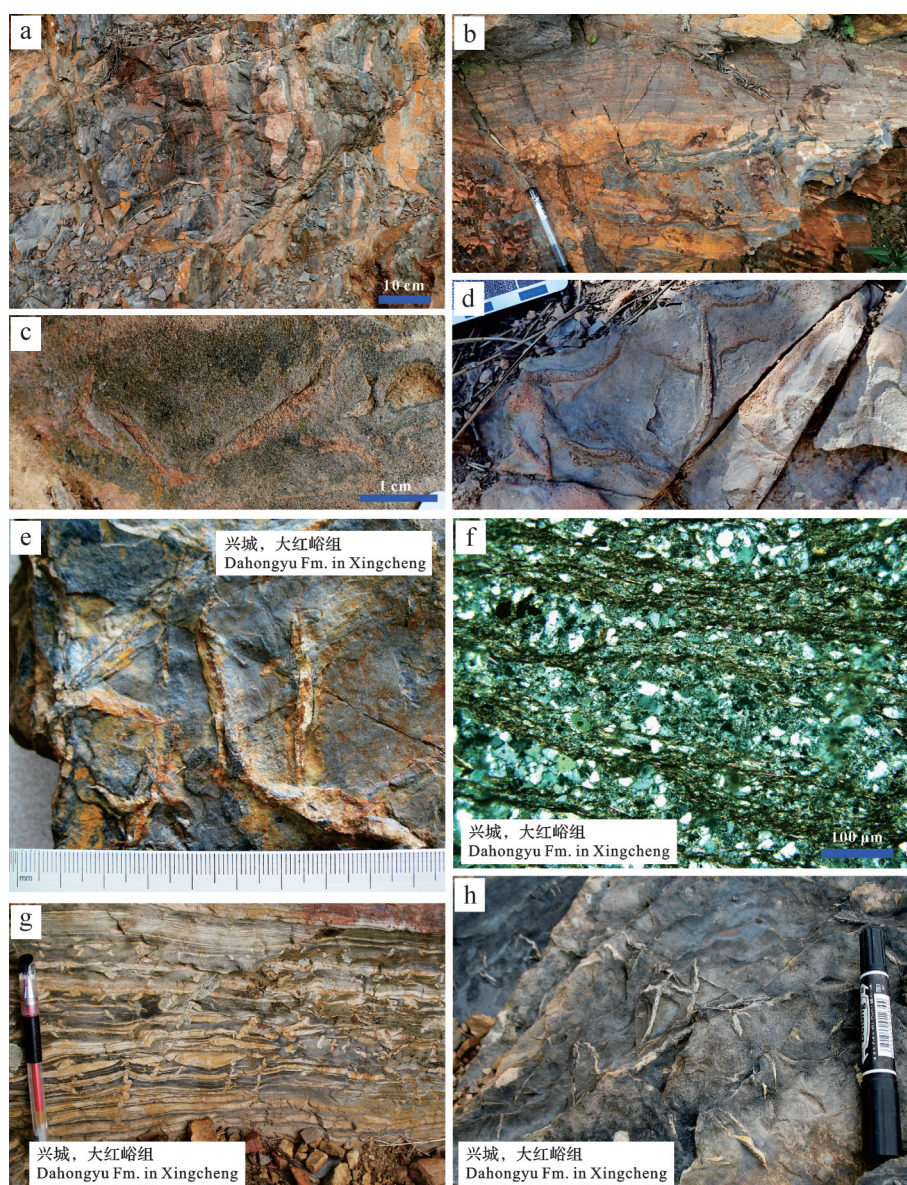


图5 兴城地区常州沟组含席裂层位沉积特征和大红峪组席裂构造

(a)常州沟组含席裂层位岩性,箭头指示席裂构造位置;(b)常州沟组同沉积软变形和小断层构造;(c)砂质充填的席裂相关裂隙,均为上层面,砂质充填向上凸起;(d)席裂中充填的砂质脉,所示为上层面;(e)大红峪组中部的席裂构造;(f)大红峪组席裂构造岩性镜下特征,可看到多个微生物席残留碎屑纹层;(g)大红峪组含席裂构造岩层侧面,古地震成因?泄水砂脉构造;(h)大红峪组席裂构造;(e)~(h)为同一层位

Fig.5 Sedimentary characteristics of the mat-crack bed in the Changzhougou Formation and in the Xingcheng area of the Dahongyu Formation

(a) lithic sequence of the crack-bearing bed of the Changzhougou Formation (arrow points to the cracks); (b) syndepositional soft deformation and small fault; (c) sand-filled cracks, upper level (sand fill is embossed); (d) sand vein in mat-crack, upper surface; (e) mat-cracks from mid-Dahongyu Formation; (f) microstructures in rock with mat-cracks from the Dahongyu Formation, showing several laminae of residues of mat; (g) side view of mat-crack bearing rock of Dahongyu Formation with many water-escape veins, possibly resulting from paleoseismic event; (h) mat-cracks in Dahongyu Formation. (Photographs (e) (f) (g) and (h) are from the same horizon and locality)

组保存席裂岩层的侧面未见明显的砂脉和震裂构造,可能说明泄水作用不强烈,也可能是出露断面的局限性所限。

席裂与泥裂也有明显区别。泥裂一般发生在细碎屑沉积物暴露在水上的环境,形成向下较深的“V”

字型裂隙(图6t),上覆岩层以铸模形式向裂隙填充^[77-79],不具有完整而平滑的微生物席降解残余碎屑层。而标准的席裂构造保存在岩层上层面上,大部分情况下微生物席埋藏降解之后会有含碳质的黏土碎屑保留纹层状的藻席结构^[8,13,80]。此外,泥裂构造因

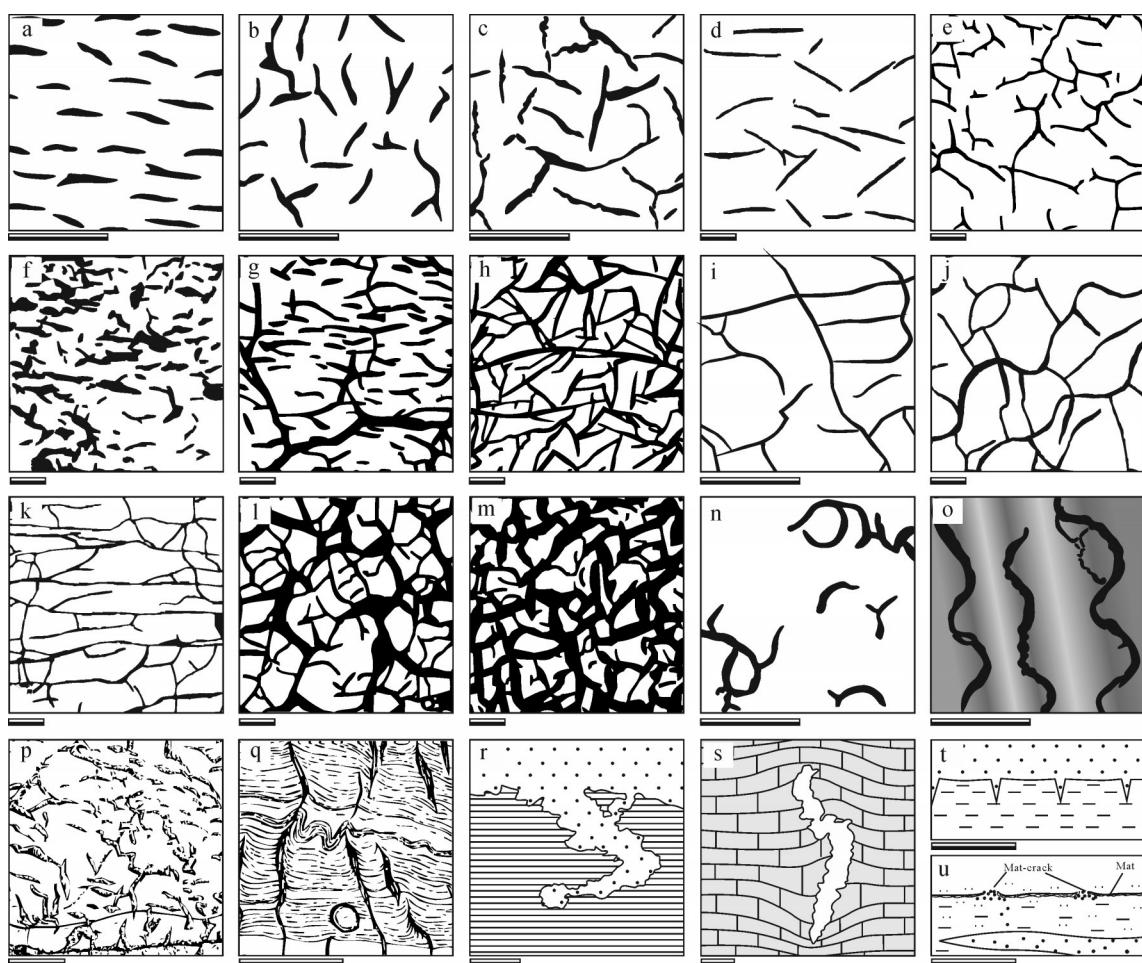


图6 沉积岩层面或剖面可见的部分典型裂隙状构造示意图(图中(a)(b)(c)(i)(n)(o)(r)(s)据 McMahon *et al.*^[77]; (d)(e)(f)(g)(h)(j)(k)(l)(m)据 Pratt^[74]; (p)(q)据乔秀夫等^[76])

(a)孤立的定向排列纺锤形;(b)分枝纺锤形和三连接鸟足状;(c)部分连接的分枝状;(d)近平行透镜状,交割;(e)不完全多边形;(f)近平行,不规则透镜状;(g)多边形及平行透镜状;(h)不规则网状和透镜状;(i)接的分支和多边形;(j)波谷正弦曲线(类似假化石 *Manchuriophycus*);(k)直角网状;(l)多边形;(m)多边形;(n)花纹状裂隙;(o)波谷正弦曲线;(p)液化脉;(q)液化脉;(r)泥岩中上下变尖的肠状褶皱砂质充填裂隙;(s)灰岩中上下变尖的肠状褶皱微粒充填裂隙(臼齿状构造),扰动了背景纹层;(t)泥裂;(u)本文描述的席裂构造侧视示意图。比例尺长5 cm

Fig.6 Sketches of typical crack structures seen on the surface and in lateral profile of sedimentary rocks: (a), (b), (c), (i), (n), (o), (r) and (s) after McMahon *et al.*^[77]; (d)-(h), (j)-(m) after Pratt^[74]; (p) and (q) after Qiao *et al.*^[76]

(a) isolated aligned spindles; (b) branching spindles and triple-junction "bird's feet"; (c) partially connected branches; (d) sub-parallel lenticular, cross-cutting; (e) incomplete polygonal; (f) sub-parallel, irregularly lenticular; (g) polygonal with parallel lenticular; (h) irregular reticulate and lenticular; (i) connected branches and polygons; (j) sinusoidal in ripple troughs (similar to *Manchuriophycus* pseudofossil); (k) orthogonal reticulate; (l) polygonal; (m) polygonal; (n) curlicue; (o) sinuous ripple-trough; (p) liquefaction veins; (q) liquefaction veins; (r) vertical cross-section of downwards-tapering, upwards-bifurcating, ptygmatically folded sand-filled crack in mudstone; (s) vertical cross-section of upwards-and downwards-tapering, ptygmatically folded microspar-filled crack ("molar tooth") in limestone, showing distortion of matrix laminae; (t) mud crack; (u) lateral profile of mat-crack described in present study. Scale bars = 5 cm

为发生在黏土质沉积表面,沉积物脱水后容易出现裂隙交割而成的多边形网络,裂隙间角度一般呈 90° ~ 120° ^[79](图4c),裂纹常常延伸较长且平直(图4c)。而微生物席的脱水收缩作用会形成一些直径3~40 cm、边缘圆状的不规则多边形(图4b)^[79]。微生物席的结构具有较强(对比碎屑沉积物)的黏性和韧性,所以在脱水不完全和不剧烈的情况下形成纺锤状裂隙(图4d,f),相互间不连通或很少连接,而且裂

隙边缘容易发生褶皱卷曲。需要注意的是,在有些情况下也有席裂和泥裂两种机制共同作用的现象^[77]。

MISS构造是一个包含广泛的统称,虽然有学者已经对其中的裂隙构造分类做了详细研究^[11,81],但主要涉及干缩程度较高的 Mat-crack polygon。微生物席收缩成因的裂隙构造在前寒武纪地层中有广泛的出现,却经常被记录为泥裂构造,这将影响对古生态和古环境的正确解释。Kovalchuk *et al.*^[79]曾用

microbially influenced desiccation cracks 表述过微生物席相关的裂隙构造, Polygonal oscillation cracks 也被作为近似术语使用过^[8]。本文描述的这种情况在宏观形态上还没有形成多边形,有孤立存在的、部分连接的、还有一些长延伸的裂隙存在,可以对应到图6中的(b)~(e)等所示的不同形态,并且本文描述的几种特征在一个层面上产出,说明他们的形成机理具有共同的部分,理应有个统一的术语来表达。为了避免过渡性特征导致的术语和实际不贴切,本文提议将这种与微生物席脱水收缩所产生的裂隙构造称为席裂(Mat-crack),与席裂多边形(Mat-crack polygon)代表收缩裂隙(Shrinkage crack)的不同发育程度,避免“泥裂状构造”、“纺锤状裂隙”、“分枝状裂隙”等纯形态表述。在进一步描述时可以使用形态+席裂的方式,比如“纺锤状席裂”。这样做有助于更准确的描述和分析沉积环境。此外,地层中各种裂隙的形态表述可以参考图6所示。有些形态可能不仅出现在有微生物席的情况,在一些砂质和泥质沉积表面也会出现,所以需要多方面论证分析。

4 古环境意义分析

海相环境微生物席大量出现在潮间带区域, Bose *et al.*^[11,81]对不同水深环境下的微生物席相关构造的特征和分布进行了归纳, Tang *et al.*^[82]又进行了部分补充。席裂多边形主要分布在潮间带上部至潮上带下部,水深20 cm左右,之下是经过搬运的微生物席砂质碎片和微皱饰构造,之上是各种上拱构造。本文描述的MISS构造岩性特征是肉红色中粗粒砂岩、细砾岩透镜体、以及灰黑色调的纹层状粉细砂岩交替产出,具透镜状层理和波纹层理,纹层厚度不规则,说明水体的运动能量较强,是典型的潮间带沉积特征^[11,48]。形成纺锤状席裂构造与席裂多边形的古环境条件接近,但影响它们张裂程度的因素可能不仅仅是古水深,光照条件、暴露时间、古气候等均需要考虑。夹山西剖面常州沟组席裂构造层位之下主要是一些滨海相的粗碎屑砂岩(图2),陆源碎屑补给多且沉积速率较高、水底冲刷频繁,不适合微生物席大量,仅有少量的、再沉积的微生物碎屑^[48]。演化至潮间带环境时,虽然水体能量依然较强,但是陆源碎屑物减少,微生物席得以大量生长繁殖,并对水底沉积物表面产生稳固作用^[11,81]。

微生物席一般需要生存在透光带内,所以在极

浅水环境下因海平面升降而时常暴露于空气下,蒸发脱水导致席裂产生^[11,81]。通过对现代微生物席的观察,发现由于脱水干燥的程度不同,干缩裂隙的形态呈现分带特征,在完全干燥的区域出现了席裂多边形(图4e),而继续有水分补给的区域则保持完好或只发育不连通的纺锤状裂隙(图4e),说明微生物席的含水性 and 活性与其抗张裂能力正相关。

5 结论

辽宁兴城夹山常州沟组砂岩层面上一些“裂隙状构造”的成因是微生物席的脱水收缩,属于MISS构造中的收缩裂隙—席裂构造。微生物席在脱水不充分的情况下形成纺锤状席裂,脱水充分的情况下形成席裂多边形,建议在术语上将它们区分。

砂岩中MISS构造的发现和识别,扩大了人们对前寒武纪生态环境和生物总量的认知。砂岩中与微生物席干缩作用相关的各种裂隙构造常见,描述和分析沉积环境时需要将其与泥裂区别开来。辽宁兴城常州沟组中的这些微生物成因沉积构造出现在潮间带环境,代表了区内最早的微生物生态系统及其与沉积过程的相互作用。微生物生命形式在华北克拉通东部中元古代海侵早期已经开始影响古海岸带的地质过程,这对于了解燕山裂陷槽盆地的生物—沉积作用和环境演化有重要意义。

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参考文献(References)

- [1] Gerdes G, Krumbein W E. Biolaminated deposits[M]. Berlin: Springer-Verlag, 1987: 1-183.
- [2] Schieber J. Possible indicators of microbial mat deposits in shales and sandstones: Examples from the Mid-Proterozoic Belt Supergroup, Montana, U. S. A. [J]. Sedimentary Geology, 1998, 120 (1/2/3/4): 105-124.
- [3] Schieber J. Microbial mats in terrigenous clastics: The challenge of identification in the rock record[J]. Palaios, 1999, 14(1): 3-12.
- [4] Gerdes G, Klenke T, Noffke N. Microbial signatures in peritidal siliciclastic sediments: A catalogue [J]. Sedimentology, 2000, 47(2): 279-308.
- [5] Noffke N, Gerdes G, Klenke T, et al. Microbially induced sedimentary structures indicating climatological, hydrological and depositional conditions within recent and Pleistocene coastal facies zones (southern Tunisia)[J]. Facies, 2001, 44(1): 23-30.

- [6] Noffke N, Gerdes G, Klenke T, et al. Microbially induced sedimentary structures: A new category within the classification of primary sedimentary structures [J]. *Journal of Sedimentary Research*, 2001, 71(5): 649-656.
- [7] Noffke N, Eriksson K A, Hazen R M, et al. A new window into Early Archean life: Microbial mats in Earth's oldest siliciclastic tidal deposits (3.2 Ga Moodies Group, South Africa) [J]. *Geology*, 2006, 34(4): 252-256.
- [8] Schieber J, Bose P K, Eriksson P G, et al. Atlas of microbial mat features preserved within the siliciclastic rock record [M]. Amsterdam: Elsevier, 2007: 1-324.
- [9] Noffke N, Paterson D. Microbial interactions with physical sediment dynamics, and their significance for the interpretation of Earth's biological history [J]. *Geobiology*, 2008, 6(1): 1-4.
- [10] Sarkar S, Bose P K, Samanta P, et al. Microbial mat mediated structures in the Ediacaran Sonia Sandstone, Rajasthan, India, and their implications for Proterozoic sedimentation [J]. *Precambrian Research*, 2008, 162(1/2): 248-263.
- [11] Bose S, Chafetz H S. Morphology and distribution of MISS: A comparison between modern siliciclastic and carbonate settings [M]//Noffke N, Chafetz H. *Microbial mats in siliciclastic depositional systems through time*. Tulsa: SEPM, 2012, 101: 3-14.
- [12] Davies N S, Liu A G, Gibling M R, et al. Resolving MISS conceptions and misconceptions: A geological approach to sedimentary surface textures generated by microbial and abiotic processes [J]. *Earth-Science Reviews*, 2016, 154: 210-246.
- [13] Noffke N. Comment on the paper by Davies et al. "Resolving MISS conceptions and misconceptions: A geological approach to sedimentary surface textures generated by microbial and abiotic processes" (*Earth Science Reviews*, 154 (2016), 210-246) [J]. *Earth-Science Reviews*, 2018, 176: 373-383.
- [14] Eriksson P G, Condie K C, Tirsgaard H, et al. Precambrian clastic sedimentation systems [J]. *Sedimentary Geology*, 1998, 120(1/2/3/4): 5-53.
- [15] Bose P K, Eriksson P G, Sarkar S, et al. Sedimentation patterns during the Precambrian: A unique record? [J]. *Marine and Petroleum Geology*, 2012, 33(1): 34-68.
- [16] Noffke N. *Geobiology: Microbial mats in sandy deposits from the Archean Era to today* [M]. Berlin Heidelberg: Springer Verlag, 2010: 1-193.
- [17] Konhauser K. *Introduction to geomicrobiology* [M]. Malden: Blackwell Science Ltd., 2007.
- [18] Seckbach J, Oren A. *Microbial mats: Modern and ancient microorganisms in stratified systems* [M]. Dordrecht: Springer, 2010: 41-51.
- [19] Reitner J, Quéric N V, Arp G. *Advances in stromatolite geobiology* [M]. Berlin Heidelberg: Springer-Verlag, 2011: 1-559.
- [20] Lu S N, Zhao G C, Wang H C, et al. Precambrian metamorphic basement and sedimentary cover of the North China Craton: A review [J]. *Precambrian Research*, 2008, 160(1/2): 77-93.
- [21] Zhao G C, Li S Z, Sun M, et al. Assembly, accretion, and break-up of the Palaeo-Mesoproterozoic Columbia supercontinent: Record in the North China Craton revisited [J]. *International Geology Review*, 2011, 53(11/12): 1331-1356.
- [22] 翟明国. 中国主要古陆与联合大陆的形成: 综述与展望 [J]. *中国科学(D辑): 地球科学*, 2013, 43(10): 1583-1606. [Zhai Mingguo. The main old lands in China and assembly of Chinese unified continent [J]. *Science China (Seri. D): Earth Sciences*, 2013, 43(10): 1583-1606.]
- [23] 张健, 田辉, 李怀坤, 等. 华北克拉通北缘 Columbia 超大陆裂解事件: 来自燕辽裂陷槽中部长城系碱性火山岩的地球化学、锆石 U-Pb 年代学和 Hf 同位素证据 [J]. *岩石学报*, 2015, 31(10): 3129-3146. [Zhang Jian, Tian Hui, Li Huaikun, et al. Age, geochemistry and zircon Hf isotope of the alkaline basaltic rocks in the middle section of the Yan-Liao aulacogen along the northern margin of the North China Craton: New evidence for the breakup of the Columbia supercontinent [J]. *Acta Petrologica Sinica*, 2015, 31(10): 3129-3146.]
- [24] 王鸿祯, 楚旭春, 刘本培, 等. *中国古地理图集* [M]. 北京: 中国地图出版社, 1985: 1-283. [Wang Hongzhen, Chu Xuchun, Liu Benpei, et al. *Atlas of the palaeogeography of China* [M]. Beijing: China Cartographic Publishing House, 1985: 1-283.]
- [25] 陈晋镛, 张惠民, 朱士兴, 等. 蓟县震旦亚界研究 [M]//中国地质科学院天津地质矿产研究所. *中国震旦亚界*. 天津: 天津科学技术出版社, 1980: 56-114. [Chen Jinbiao, Zhang Huimin, Zhu Shixing, et al. *Research on Sinian suberathem of Jixian*, Tianjin [M]//Tianjin Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences. *Sinian suberathem in China*. Tianjin: Tianjin Science and Technology Press, 1980: 56-114.]
- [26] Zhu S X, Sun S F, Huang X G, et al. Discovery of carbonaceous compressions and their multicellular tissues from the Changzhongou Formation (1800 Ma) in the Yanshan Range, North China [J]. *Chinese Science Bulletin*, 2000, 45(9): 841-847.
- [27] Peng Y B, Bao H M, Yuan X L. New morphological observations for Paleoproterozoic acritarchs from the Chuanlinggou Formation, North China [J]. *Precambrian Research*, 2009, 168(3/4): 223-232.
- [28] Lamb D M, Awramik S M, Chapman D J, et al. Evidence for eukaryotic diversification in the ~1800 million-year-old Changzhongou Formation, North China [J]. *Precambrian Research*, 2009, 173(1/2/3/4): 93-104.
- [29] Zhu S X, Zhu M Y, Knoll A H, et al. Decimetre-scale multicellular eukaryotes from the 1.56-billion-year-old Gaoyuzhuang Formation in North China [J]. *Nature Communication*, 2016, 7: 11500.
- [30] 国家地质总局天津地质矿产研究所, 中国科学院南京地质古生物研究室, 内蒙古自治区地质局. 蓟县震旦亚界叠层石的

- 研究[M]. 北京:地质出版社,1979:39-48. [Tianjin Institute of Geology and Mineral Resources, State Bureau of Geology, Nanjin Institute of Geology and Palaeontology, Academy Sinica, Geology Bureau of Inner Mongolian Autonomous Region. Studies on stromatolites from Sinian suberathem in Jixian area[M]. Beijing: Geological Publishing House, 1979: 39-48.]
- [31] 孟祥化,葛铭. 中朝板块旋回层序、事件和形成演化的探索[J]. 地学前缘,2002,9(3):125-140. [Meng Xianghua, Ge Ming. Research on cyclic sequence, events and formational evolution of the Sino-Korea plate[J]. Earth Science Frontiers, 2002, 9(3): 125-140.]
- [32] Chu X L, Zhang T G, Zhang Q R, et al. Sulfur and carbon isotope records from 1700 to 800 Ma carbonates of the Jixian section, northern China: Implications for secular isotope variations in Proterozoic seawater and relationships to global supercontinental events[J]. *Geochimica et Cosmochimica Acta*, 2007, 71(19): 4668-4692.
- [33] Zhang K, Zhu X K Wood R A, et al. Oxygenation of the Mesoproterozoic ocean and the evolution of complex eukaryotes[J]. *Nature Geoscience*, 2018, 11(5): 345-350.
- [34] Noffke N, Gerdes G, Klenke T. Benthic cyanobacteria and their influence on the sedimentary dynamics of peritidal depositional systems (siliciclastic, evaporitic salty, and evaporitic carbonatic)[J]. *Earth-Science Reviews*, 2003, 62(1/2): 163-176.
- [35] 梅冥相,高金汉,孟庆芬. 从席底构造到第五类原生沉积构造:沉积学中具有重要意义的概念[J]. 现代地质,2006,20(3):413-422. [Mei Mingxiang, Gao Jinhan, Meng Qingfen. From matground structures to the primary sedimentary structures of a fifth category: Significant concepts on sedimentology[J]. *Geoscience*, 2006, 20(3): 413-422.]
- [36] 郭荣涛. 硅质碎屑岩中的微生物席相关构造:联接现代与过去的纽带[J]. 地球科学进展,2013,28(4):467-476. [Guo Rongtao. The mat related structures preserved within siliciclastic rock record: The connection of now and past[J]. *Advances in Earth Science*, 2013, 28(4): 467-476.]
- [37] 梅冥相,孟庆芬,高金汉. 前寒武纪海侵砂岩中的微生物砂质碎片:以北京南口虎峪剖面大红峪组为例[J]. 地学前缘,2007,14(2):197-204. [Mei Mingxiang, Meng Qingfen, Gao Jinhan. Microbial sand chips in transgressive sandstones of the Precambrian: An example from the Dahongyu Formation at the Huyu section of the Nankou town in Beijing[J]. *Earth Science Frontiers*, 2007, 14(2): 197-204.]
- [38] 史晓颖,王新强,蒋干清,等. 贺兰山地区中元古代微生物席成因构造:远古时期微生物群活动的沉积标识[J]. 地质论评,2008,54(5):575-586. [Shi Xiaoying, Wang Xinqiang, Jiang Ganqing, et al. Pervasive microbial mat colonization on Mesoproterozoic peritidal siliciclastic substrates: An example from the Huangqikou Formation (ca 1.6 Ga) in Helan Mountains, NW China[J]. *Geological Review*, 2008, 54(5): 577-586.]
- [39] 郑元,吕洪波,章雨旭,等. 山西黎城中元古代砂岩层面多种痕迹特征及成因初析[J]. 地质论评,2009,55(1):1-9. [Zheng Yuan, Lü Hongbo, Zhang Yuxu, et al. Miscellaneous traces on the bedding planes of Mesoproterozoic sandstones in Licheng, Shanxi: characteristics and origin analysis[J]. *Geological Review*, 2009, 55(1): 1-9.]
- [40] 郑伟,孙凤余. 豫西鲁山汝阳群微生物成因构造宏观特征分析及其环境演化[J]. 地质调查与研究,2011,34(3):170-178. [Zheng Wei, Sun Fengyu. Macro-analysis on the microbially induced sedimentary structures features and the sedimentary environmental evolution in the Ruyang Group of Lushan, western Henan[J]. *Geological Survey and Research*, 2011, 34(3): 170-178.]
- [41] 邢智峰,齐永安,郑伟,等. 从微观角度认识微生物席在中元古代的繁盛:以豫西云梦山组为例[J]. 沉积学报,2011,29(5):857-865. [Xing Zhifeng, Qi Yong'an, Zheng Wei, et al. Microscopic characteristics of extensive microbial mats in Mesoproterozoic Era: An example from the Yunmengshan Formation, western Henan[J]. *Acta Sedimentologica Sinica*, 2011, 29(5): 857-865.]
- [42] 陈留勤. 河北兴隆中元古界大红峪组微生物成因构造特征及其地质意义[J]. 岩石矿物学杂志,2013,32(3):366-372. [Chen Liuqin. Characteristics and geological significance of Microbially Induced Sedimentary Structures (MISS) in Mesoproterozoic Dahongyu Formation of Xinglong county, Hebei province[J]. *Acta Petrologica et Mineralogica*, 2013, 32(3): 366-372.]
- [43] 郑伟,邢智峰. 山西黎城中元古界常州沟组微生物成因构造(MISS)及其地质意义[J]. 现代地质,2015,29(4):825-832. [Zheng Wei, Xing Zhifeng. Characteristics and geological significance of Microbially Induced Sedimentary Structures (MISS) in Changzhougou Formation of Mesoproterozoic in Licheng county, Shanxi province[J]. *Geoscience*, 2015, 29(4): 825-832.]
- [44] Yang H, Chen Z Q, Fang Y H. Microbially induced sedimentary structures from the 1.64 Ga Chuanlinggou Formation, Jixian, North China[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2017, 474: 7-25.
- [45] Zhu S X, Cheng H N. Megascopic multicellular organisms from the 1700-million-year-old Tuanshanzi Formation in the Jixian area, North China[J]. *Science*, 1995, 270(5236): 620-622.
- [46] Lamb D M, Awramik S M, Zhu S. Paleoproterozoic compression-like structures from the Changzhougou Formation, China: Eukaryotes or clasts?[J]. *Precambrian Research*, 2007, 154(3/4): 236-247.
- [47] 刘鹏举. 燕山地区中元古代常州沟组潜穴化石[J]. 地质论评,2003,49(5):522-524. [Liu Pengju. Burrow fossils in the Changzhougou Formation of the Mesoproterozoic in the Yan-shan area[J]. *Geological Review*, 2003, 49(5): 522-524.]
- [48] 于晓辉,沈军,林玲玲,等. 辽宁中元古代初期粗碎屑岩中微

- 生物砂质颗粒的发现及古环境意义[J]. 地学前缘, 2016, 23(4): 284-291. [Yu Xiaohui, Shen Jun, Lin Lingling, et al. The discovery of microbial debris in the coarse elastic rock of the Early Mesoproterozoic in Liaoning province, China and its paleoenvironmental significance [J]. Earth Science Frontiers, 2016, 23(4): 284-291.]
- [49] 吴福元, 杨进辉, 张艳斌, 等. 辽西东南部中生代花岗岩时代[J]. 岩石学报, 2006, 22(2): 315-325. [Wu Fuyuan, Yang Jinhui, Zhang Yanbin, et al. Emplacement ages of the Mesozoic granites in southeastern part of the western Liaoning province [J]. Acta Petrologica Sinica, 2006, 22(2): 315-325.]
- [50] 张梅生, 王锡魁, 郭巍, 等. 地球科学野外实习指导书: 兴城地质[M]. 北京: 地质出版社, 2013: 1-181. [Zhang Meisheng, Wang Xikui, Guo Wei, et al. Instructor book of earth science field study: Geology on Xingcheng [M]. Beijing: Geological Publishing House, 2013: 1-181.]
- [51] 王旖旎, 张梅生, 李晓波, 等. 辽宁兴城夹山地区中元古界团山子组叠层石的发现及其地层学意义[J]. 吉林大学学报(地球科学版), 2012, 42(增刊1): 336-343. [Wang Yini, Zhang Meisheng, Li Xiaobo, et al. Discovery of Mesoproterozoic stromatolites from the Tuanshanzi Formation of Changcheng System and its stratigraphical significance in Jiashan area of Xingcheng, Liaoning province [J]. Journal of Jilin University (Earth Science Edition), 2012, 42(Suppl. 1): 336-343.]
- [52] Wang Y N, Zhang M S, Li X B, et al. The sedimentary record of a Mesoproterozoic tsunami from the North China Craton[J]. Geological Journal, 2015, 50(1): 56-70.
- [53] 张旻旻, 张梅生, 李晓波, 等. 辽西兴城地区上古生界沉积环境识别[J]. 沉积学报, 2015, 33(6): 1159-1169. [Zhang Minmin, Zhang Meisheng, Li Xiaobo, et al. Recognition on sedimentary environment of Upper Paleozoic in Xingcheng, western Liaoning [J]. Acta Sedimentologica Sinica, 2015, 33(6): 1159-1169.]
- [54] Yang M, Zhang M S, Li X B, et al. A mesoproterozoic palaeokarst on the North China Craton in the Xingcheng area of Liaoning province, China: Characteristics and significance on paleogeography[J]. International Geology Review, 2019, 61(5): 637-648.
- [55] 张栋, 张梅生, 王旖旎, 等. 辽宁兴城龙回头盆地海房沟组地层序列及沉积环境研究[J]. 地质与勘探, 2012, 48(2): 227-236. [Zhang Dong, Zhang Meisheng, Wang Yini, et al. Stratigraphic sequence and sedimentary environment of the Haifanggou Formation in the Longhuitou Basin of Xingcheng, Liaoning province [J]. Geology and Exploration, 2012, 48(2): 227-236.]
- [56] 张乾, 张梅生, 李晓波, 等. 辽宁西部兴城曹庄地区义县组岩石地层序列及锆石 U-Pb 年龄[J]. 世界地质, 2016, 35(1): 51-65. [Zhang Qian, Zhang Meisheng, Li Xiaobo, et al. Stratigraphic sequences and zircon U-Pb dating of Yixian Formation in Caozhuang area of Xingcheng, western Liaoning [J]. Global Geology, 2016, 35(1): 51-65.]
- [57] 孙敬书, 王敏成, 任福顺. 辽宁建昌八家子地区中元古界[J]. 中国区域地质, 1990, 9(3): 206-214. [Sun Jingshu, Wang Mincheng, Ren Fushun. The Middle Proterozoic in the Bajiazi area, Jianchang, Liaoning province [J]. Regional Geology of China, 1990, 9(3): 206-214.]
- [58] 和政军, 孟祥化, 葛铭. 燕山地区长城纪沉积演化及构造背景[J]. 沉积学报, 1994, 12(2): 10-19. [He Zhengjun, Meng Xianghua, Ge Ming. 1994. Environmental evolutions and structural control of Changchengian of the Mid-Proterozoic in the Yanshan Basin, North China [J]. Acta Sedimentologica Sinica, 1994, 12(2): 10-19.]
- [59] 曲永强, 孟庆任, 马收先, 等. 华北地块北缘中元古界几个重要不整合面的地质特征及构造意义[J]. 地学前缘, 2010, 17(4): 112-127. [Qu Yongqiang, Meng Qingren, Ma Shouxian, et al. Geological characteristics of unconformities in Mesoproterozoic successions in the northern margin of North China Block and their tectonic implications [J]. Earth Science Frontiers, 2010, 17(4): 112-127.]
- [60] 张梅生, 李晓波, 王旖旎, 等. 地质专报: 1:25万锦西市幅区域地质调查报告[R]. 2016. [Zhang Meisheng, Li Xiaobo, Wang Yini, et al. Geological report: geological survey report of 1:250000 Jinxi city map area [R]. 2016.]
- [61] 和政军. 辽宁锦西地区中元古代—中生代砂岩构造背景的探讨[J]. 沉积学报, 1989, 7(2): 21-28. [He Zhengjun. Approach of tectonic background for Mid Proterozoic Mesozoic sandstones in Jinxi, Liaoning [J]. Acta Sedimentologica Sinica, 1989, 7(2): 21-28.]
- [62] 和睦. 葫芦岛地区长城系常州沟组-团山子组沉积环境的初步分析[J]. 辽宁地质, 1984(1): 51-62. [He Mu. The preliminary analysis on sedimentary environment from Changzhougou Formation-Tuanshanzi Formation Changcheng System in Huludao region [J]. Liaoning Geology, 1984(1): 51-62.]
- [63] 杨明春, 郑常青, 张梅生, 等. 辽宁兴城地区中元古界长城系大红峪组石英砂岩质砾岩古沉积环境研究[J]. 矿物岩石, 2012, 32(3): 103-109. [Yang Mingchun, Zheng Changqing, Zhang Meisheng, et al. Study on paleo-sedimentary environment of Dahongyu Formation sandstone conglomerate of Changcheng System of Mesoproterozoic in Xingcheng area, Liaoning province [J]. Journal of Mineralogy and Petrology, 2012, 32(3): 103-109.]
- [64] 常绍泉, 张维芳, 汪凤鸣, 等. 辽宁锦西葫芦岛的元古界并论兴城运动的意义[J]. 辽宁地质学报, 1984(1): 1-6. [Chang Shaoquan, Zhang Weifang, Wang Fengming. On Middle Proterozoic in Huludao peninsula of Jinxixian, Liaoning with discussion about Xingcheng Movement and its significance [J]. Acta Geologica Liaoning, 1984(1): 1-6.]
- [65] 刘波, 李铨, 陈晋铤, 等. 辽宁兴城小盖州地区元古宙火山岩及扇—三角洲沉积[J]. 辽宁地质, 1994(1/2): 21-29. [Liu Bo, Li Quan, Chen Jinbiao, et al. The Proterozoic volcanic rocks

- and fan-delta deposits in Xiaogaizhou section, Xingcheng county, Liaoning[J]. *Liaoning Geology*, 1994(1/2): 21-29.]
- [66] 张丛,郭巍,于松,等. 辽宁兴城地区长城系团山子组与大红峪组不整合接触特征及其对兴城运动的意义[J]. *世界地质*, 2016, 35(4): 1027-1033. [Zhang Cong, Guo Wei, Yu Song, et al. Unconformity between Tuanshanzi and Dahongyu formations of Changcheng Group in Xingcheng, Liaoning province and its significance for Xingcheng Movement[J]. *Global Geology*, 2016, 35(4): 1027-1033.]
- [67] 李晓波,王旖旎,杨明,等. 辽宁兴城中元古界大红峪组石英砂岩中保存的微生物席构造(英文)[C]//中国古生物学会第26届学术年会论文集. 贵州:中国古生物学会, 2011. [Li Xiaobo, Wang Yini, Yang Ming, et al. Microbial mat features preserved within the mesoproterozoic sandstone rocks (~1.6Ga in Xingcheng area, Liaoning province, P. R. China)[C]//Abstract of the 26th annual conference of the paleontological society of China. Guizhou: Palaeontological Society of China, 2011.]
- [68] 梅冥相,孟庆芬,刘智荣. 微生物形成的原生沉积构造研究进展综述[J]. *古地理学报*, 2007, 9(4): 353-367. [Mei Mingxiang, Meng Qingfen, Liu Zhirong. Overview of advances in studies of primary sedimentary structures formed by microbes[J]. *Journal of Palaeogeography*, 2007, 9(4): 353-367.]
- [69] 乔秀夫,高林志. 燕辽裂陷槽中元古代古地震与古地理[J]. *古地理学报*, 2007, 9(4): 337-352. [Qiao Xiufu, Gao Linzhi. Mesoproterozoic palaeoearthquake and palaeogeography in Yan-Liao Aulacogen[J]. *Journal of Palaeogeography*, 2007, 9(4): 337-352.]
- [70] 刘洪福,刘池洋. 蓟县中元古界长城群串岭沟组中发现最古老的后生动物遗迹化石[J]. *西北大学学报(自然科学版)*, 1992, 22(3): 268. [Liu Hongfu, Liu ChiYang. The discovery of the Oldest Metazoan trace fossils in Chuan Linggou Formation of Changcheng Group in the Jixian stratotype[J]. *Journal of Northwest University (Natural Science Edition)*, 1992, 22(3): 268.]
- [71] Xiao S H, Laflamme M. On the eve of animal radiation: Phylogeny, ecology and evolution of the Ediacara biota[J]. *Trends in Ecology & Evolution*, 2009, 24(1): 31-40.
- [72] 史晓颖,蒋干清,张传恒,等. 华北地台中元古代串岭沟组页岩中的砂脉构造:17亿年前甲烷气逃逸的沉积标识?[J]. *地球科学——中国地质大学学报*, 2008, 33(5): 577-590. [Shi Xiaoying, Jiang Ganqing, Zhang Chuanheng, et al. Sand veins and microbially induced sedimentary structures from the black shale of the Mesoproterozoic Chuanlinggou Formation(ca. 1.7 Ga) in North China: implications for methane degassing from Microbial Mats[J]. *Earth Science—Journal of China University of Geosciences*, 2008, 33(5): 577-590.]
- [73] 汤冬杰,史晓颖,刘娟,等. 华北地台串岭沟组砂脉中自生碳酸盐沉淀和自生黄铁矿:中元古代甲烷厌氧氧化的沉积证据[J]. *古地理学报*, 2009, 11(4): 361-374. [Tang Dongjie, Shi Xiaoying, Liu Juan, et al. Authigenic carbonate precipitation and pyrites from sand-veins in the Chuanlinggou Formation of the North China Platform: Evidence for anaerobic oxidation of methane in the Mesoproterozoic[J]. *Journal of Palaeogeography*, 2009, 11(4): 361-374.]
- [74] Pratt B R. Syneresis cracks: Subaqueous shrinkage in argillaceous sediments caused by earthquake-induced dewatering[J]. *Sedimentary Geology*, 1998, 117(1/2): 1-10.
- [75] Shen B, Dong L, Xiao S H, et al. Molar tooth carbonates and benthic methane fluxes in Proterozoic oceans[J]. *Nature Communications*, 2016, 7: 10317.
- [76] 乔秀夫,李海兵,高林志. 华北地台震旦纪—早古生代地震节律[J]. *地学前缘*, 1997, 4(3/4): 155-160. [Qiao Xiufu, Li Haibing, Gao Linzhi. Sinian-Early Paleozoic seismic rhythms on the North China Platform[J]. *Earth Science Frontiers*, 1997, 4(3/4): 155-160.]
- [77] McMahon S, van Smeerdijk Hood A, McIlroy D. The origin and occurrence of subaqueous sedimentary cracks[M]//Brasier A T, McIlroy D, McLoughlin N. Earth system evolution and early life: A celebration of the work of martin brasier. Geological Society, London, Special Publications, 2016, 448: 285-309.
- [78] Weinberger R. Initiation and growth of cracks during desiccation of stratified muddy sediments[J]. *Journal of Structural Geology*, 1999, 21(4): 379-386.
- [79] Kovalchuk O, Owttrim G W, Konhauser K O, et al. Desiccation cracks in siliciclastic deposits: Microbial mat-related compared to abiotic sedimentary origin[J]. *Sedimentary Geology*, 2017, 347: 67-78.
- [80] Noffke N, Beukes N, Bower D, et al. An actualistic perspective into Archean worlds – (cyano-) bacterially induced sedimentary structures in the siliciclastic Nhlazatse Section, 2.9 Ga Pongola Supergroup, South Africa[J]. *Geobiology*, 2008, 6(1): 5-20.
- [81] Bose S, Chafetz H S. Topographic control on distribution of modern microbially induced sedimentary structures (MISS): A case study from Texas coast[J]. *Sedimentary Geology*, 2009, 213(3/4): 136-149.
- [82] Tang D J, Shi X Y, Jiang G Q, et al. Morphological association of microbially induced sedimentary structures (MISS) as a paleoenvironmental indicator: An example from the Proterozoic succession of the southern North China Platform[C]//Microbial mats in siliciclastic depositional systems through time. Tulsa: SEPM, 2012: 163-175.

Microbially Induced Sedimentary Structures (MISS) in Mesoproterozoic Changzhougou Formation Sandstone, Xingcheng Area, Liaoning Province, China

LI XiaoBo^{1,2}, WANG YiNi¹, WANG Han¹

1. College of Earth Sciences, Jilin University, Changchun 130061, China

2. Department of Biology, University of Toronto Mississauga, Ontario L5L 1C6, Canada

Abstract: Numerous crack structures are found in the intertidal facies sandstone of the Mesoproterozoic Changzhougou Formation in Jiashan, Xingcheng area, Liaoning Province. The structures comprise 0.8-3.0 cm spindle-shaped short cracks, and extended cracks over 7 cm long. They are mainly isolated, some partially connected. By comparing them with other similar surface crack structures and the desiccation cracks developed in modern microbial mats, they are explained as shrinkage cracks in microbial mats (‘mat-cracks’). Unconnected spindle-shaped mat-cracks indicate incomplete mat shrinkage; mat-crack polygons form when shrinkage is complete. The presence of MISS indicates that the microbial ecosystem was already affecting the paleocoastal geological processes during the early transgression stage of the North China Craton in the Mesoproterozoic. This information is crucial for reconstructing the biosedimentary mechanisms and paleoenvironment of the aulacogenic Yanshan Basin during its early evolution.

Key words: mat-crack; paleoenvironment; intertidal; Precambrian; Changchengian System