碳酸盐岩中燧石条带成因争鸣

——以北京西山中元古界雾迷山组为例

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内容提要：北京地区中元古界雾迷山组主要由燧石条带白云岩、燧石结核白云岩、叠层石白云岩和少量含陆源粉砂质碎屑的白云岩组成，广泛出露于北京山区，厚度2000～3500 m。以雾迷山组为代表的大量中元古代硅质沉积物的物源和形成原因，一般教科书均认为层状燧石为生物成因，结核状燧石为成岩交代成因。笔者等在北京西山等地多次野外考察发现，二维剖面上的硅质条带或硅质结核在三维实体上实际上是透镜状或席状（下一般称燧石席或硅胶席）。燧石席内部常包裹或胶结有下伏白云岩的砾石并且因混有有机质等，表现为各种暗色或杂色。硅胶席在上覆白云质沉积物堆积之前与其周围的白云质灰泥和粒屑几乎同时形成，燧石透镜体与白云质沉积物之间存在着相互穿插、包裹的关系，但彼此之间边界清晰，无论是白云石粒屑还是燧石席都没有任何被交代痕迹。因此，笔者等认为：燧石"结核"是硅胶聚集成席，再经压实、固化的结果，其浑圆状边缘是水下硅胶与沉积介质的相变面。硅胶固化作用是北京西山中元古界雾迷山组中原生燧石的唯一成因。在成岩重力压实过程中，连续分布的原生硅质沉积物会形成布丁或"结核"构造。白云质灰泥和粒屑的胶结速度明显快于硅胶的固化速度，遇地震等外力作用，软的硅胶席会沿着弱固结的白云岩裂隙向上侵入或向下挤入，形成硅质脉。遇有后期的岩浆侵入或热变质作用的改造，硅质条带和硅质结核的成分和颜色会发生相应的变化，质地变纯，颜色由深变浅，但是仍然保留原生的层理或纹理，容易被误认为是成岩期或成岩后硅质交代碳酸盐矿物而成。

关键词：燧石条带；燧石结核；白云岩；硅胶席；半固结；交代作用

燧石主要由玉髓和微晶石英组成，化学成份为SiO_2，是最重要的硅质岩。自然界中，燧石呈层状、条带状和结核状分布在多个地质时代的碳酸盐岩中（叶连俊，1945；赵澄林，2001；杜远生等，2013）。

近年来，对于碳酸盐岩地层中薄层状或条带状燧石的成因多认为是生物成因，少数为特殊环境的化学沉淀和地下热泉、火山作用的产物。目前，许多权威的中、英文教科书或辞典等几乎一致认为结核状燧石是成岩后已经固结的碳酸盐矿物被硅质交代形成。例如，在*Sedimentary Geology：An Introduction to Sedimentary Rocks and Stratigraphy*（Prothero，2014[279]）和*Earth：Portrait of a Planet*（Marshak，2015[214]）两书中均认为交代作用是形成燧石结核的唯一原因；*Earth：An Introduction to Physical Geology*（Tarbuck and Lutgens，2017）中认为层状的燧石为生物成因，结核状燧石为交代成因。近年来出版的中文教材大多也采用了类似的解释（如：于炳松和梅冥相，2016[282，288]）。

中元古界雾迷山组在京西的门头沟和房山地区厚2000 m左右，主要由白云岩构成（占89%），燧石条带和燧石结核等硅质岩成分占10%（鲍亦冈，1996）。笔者等在北京西山等地多次野外考察，特别是，门头沟庄户洼村附近的永定河谷（中心点参考坐标为：北纬40°2′51″，东经115°49′34″）露头十分清晰，可以看到许多三维实体，发现剖面上的硅质条带或硅质结核，在三维实体中实际上是席状燧石与碳酸盐岩互层。燧石席内部常包裹或胶结有下伏白云岩的砾石，燧石透镜体与白云质沉积物之间存

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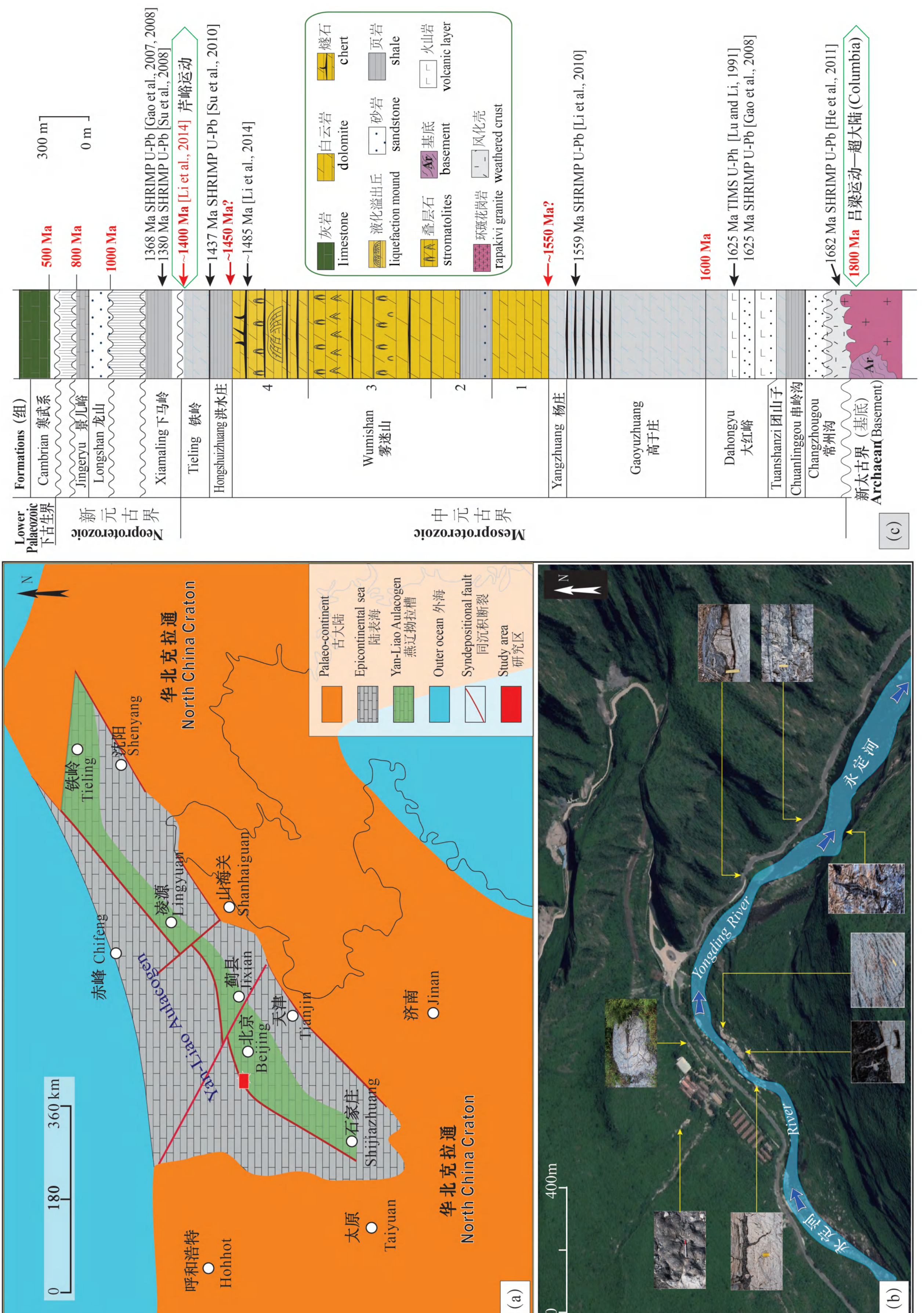


(a)
N
0 180 360 km
华北克拉通 North China Craton
Yan-Liao Aulacogen
赤峰 Chifeng
沈阳 Shenyang
铁岭 Tieling
凌源 Lingyuan
山海关 Shanhaiguan
蓟县 Jixian
北京 Beijing
天津 Tianjin
石家庄 Shijiazhuang
济南 Jinan
太原 Taiyuan
呼和浩特 Hohhot
Palaeo-continent 古大陆
Epicontinental sea 陆表海
Yan-Liao Aulacogen 燕辽拗拉槽
Outer ocean 外海
Syndepositional fault 同沉积断裂
Study area 研究区
(b)
N
0 400m
Yongding River
永定河
(c)
Lower Palaeozoic 下古生界
Neoproterozoic 新元古界
Mesoproterozoic 中元古界
新太古界（基底） Archaean(Basement)
Formations（组）
Cambrian 寒武系
Jingeryu 景儿峪
Longshan 龙山
Xiamaling 下马岭
Tieling 铁岭
Hongshuizhuang 洪水庄
Wumishan 雾迷山
Yangzhuang 杨庄
Gaoyuzhuang 高于庄
Dahongyu 大红峪
Tuanshanzi 团山子
Chuanlinggou 串岭沟
Changzhougou 常州沟
500 Ma
800 Ma
1000 Ma
1368 Ma SHRIMP U-Pb [Gao et al., 2007, 2008]
1380 Ma SHRIMP U-Pb [Su et al., 2008]
~1400 Ma [Li et al., 2014] 芹峪运动
1437 Ma SHRIMP U-Pb [Su et al., 2010]
~1450 Ma?
~1485 Ma [Li et al., 2014]
~1550 Ma?
1559 Ma SHRIMP U-Pb [Li et al., 2010]
1600 Ma
1625 Ma TIMS U-Pb [Lu and Li, 1991]
1625 Ma SHRIMP U-Pb [Gao et al., 2008]
1682 Ma SHRIMP U-Pb [He et al., 2011]
1800 Ma 吕梁运动—超大陆(Columbia)
300 m
0 m
灰岩 limestone
白云岩 dolomite
燧石 chert
液化溢出丘 liquefaction mound
砂岩 sandstone
页岩 shale
叠层石 stromatolites
基底 basement
火山岩 volcanic layer
环斑花岗岩 rapakivi granite
风化壳 weathered crust

图 1 北京西山及邻区古地理背景：(a) 中元古代燕辽裂陷槽古地理图(据何政军等,2000;乔秀夫和高林志,2007;苏德辰和孙爱萍,2011,2014);(b)庄户洼剖面典型沉积现象位置;(c) 燕辽拗拉槽地层柱状图(地层柱中地层厚度未按实际比例),庄户洼剖面位于地层柱雾迷山组第 4 段

Fig. 1 The paleogeographic background of Western Hills, Beijing, and adjacent areas: (a) Palaeogeographical map of the Yanshan Mountains—western Liaoning Aulacogen from the Mesoproterozoic Gaoyuzhuang Stage to the Wumishan Stage, showing an epicontinental sea opened to the north (after He Zhengjun et al., 2000&; Qiao Xiufu and Gao Linzhi, 2007&; Su Dechen and Sun Aiping, 2012&). The studied outcrop of the present contribution is marked by the red rectangle. (b) The location of typical sedimentary phenomena in the Zhuanghuwa Village; (c) Lithostratigraphy of the Meso-and Neoproterozoic strata of the Yanshan Mountains—western Liaoning Aulacogen and the approximate position of the study area (the Member 4, Wumishan Fm.). All the newly published SHRIMP age data are shown on the right of the column

在着相互穿插、包裹的关系,但彼此之间边界清晰,无论是白云石粒屑还是燧石席都没有任何被交代痕迹。用传统的成岩交代说根本无法解释。故本文以北京西山中元古界雾迷山组野外露头为主,结合少量其他地方的实例,讨论白云岩中的燧石条带、燧石席及其相互关系,探讨碳酸盐岩中的燧石条带或燧石席的成因。

1　地质背景

燕山—辽西中元古代裂陷槽以天津蓟县为中心,累计沉积形成的地层厚度 9000 余米。其中,凌源—平泉—兴隆—密云—涞源一线为北东向的轴部同沉积断裂带(图 1a)(和政军等,2000a;苏德辰和孙爱萍,2011;Su Dechen et al., 2014)。

雾迷山组(“雾迷山灰岩”)的命名地在原天津蓟县城西 10 余千米的无名山(Kao(高振西) et al. 1934;田树信和翟子梅,1996[29])。雾迷山组主要由燧石条带白云岩、叠层石白云岩、沥青质白云岩及少量泥状含粉砂质碎屑白云岩、硅质岩组成,以沉积韵律明显、富含燧燧石和叠层石为特征。

雾迷山期的陆表海水域开阔,水位极浅但变化频繁,浅水相的沉积构造和沉积韵律非常明显(图 2)。雾迷山组中叠层石非常发育,有多种原生叠层石生长的纹层。在叠层石生长过程中因波浪等机械作用而破碎,有大量浅水动荡标志的沉积构造,如形态完好的小型波痕和干涉波痕、泥裂构造、白云岩碎屑沉积形成的前积纹理等。根据区域地质资料,雾迷山组中、下部地层中含有少量海相石英砂岩(北京市地质矿产局,1991)。作者在野外观察发现有大量白云质内碎屑砾石,岩石薄片观察有丰富的反复搬运过的白云石和石英颗粒。无论宏观还是微观都显示了很多颗粒已经磨圆,而且颗粒大小混杂,为机械搬运后再沉积的结果(图 2)。大量波痕、泥裂的存在说明当时白云岩沉积环境为碳酸盐台地,水体极浅,甚至位于平缓的潮间带到潮下带环境。

门头沟庄户洼附近的地层中有三叠纪辉长岩、花岗斑岩和闪长玢岩侵入体,并大多以岩床形式顺层侵入(郑桂森和方景玲,1994)。

2　庄户洼剖面雾迷山组燧石特征

庄户洼附近的雾迷山组总厚度约为 2000 m。地层中含有大量黑色的燧石夹层(图 2a、b)、条带、团块。白云岩岩层之间往往发育燧石夹层(图 2c),剖面上的燧石团块,在三维露头上事实上是连续的燧石层(图 2d)或者像网脉一样沿层面彼此相联(图 2e、f)。雾迷山组中所有燧石层出现的层位均含有明显的浅水相沉积特征,如波幅极小的波痕(图 2g)、干涉波痕(图 2h)、龟裂、斜层理等(Su Dechen and Sun Aiping, 2012;Su Dechen et al., 2014),这些浅水的波痕、斜层理等完全由白云质的砂屑和砾屑构成。

在燧石层内部经常含有棱角分明、大小混杂的下伏白云岩角砾(图 3a、b)。这种现象与夏邦栋(1965)在江苏宁镇山脉古生代碳酸盐地层中的观察到的燧石结核产状几乎完全一样。另外,在层面下方的裂缝中,见到硅质岩贯入充填的现象(图 3b)。即使在完全包裹在白云岩层中的硅质岩团块内,也可见到白云岩的砾石,砾石与硅质岩之间的边界清晰,但是硅质岩与外围白云岩之间的界线有明显凹凸变化。图 3c 红色箭头处,粒

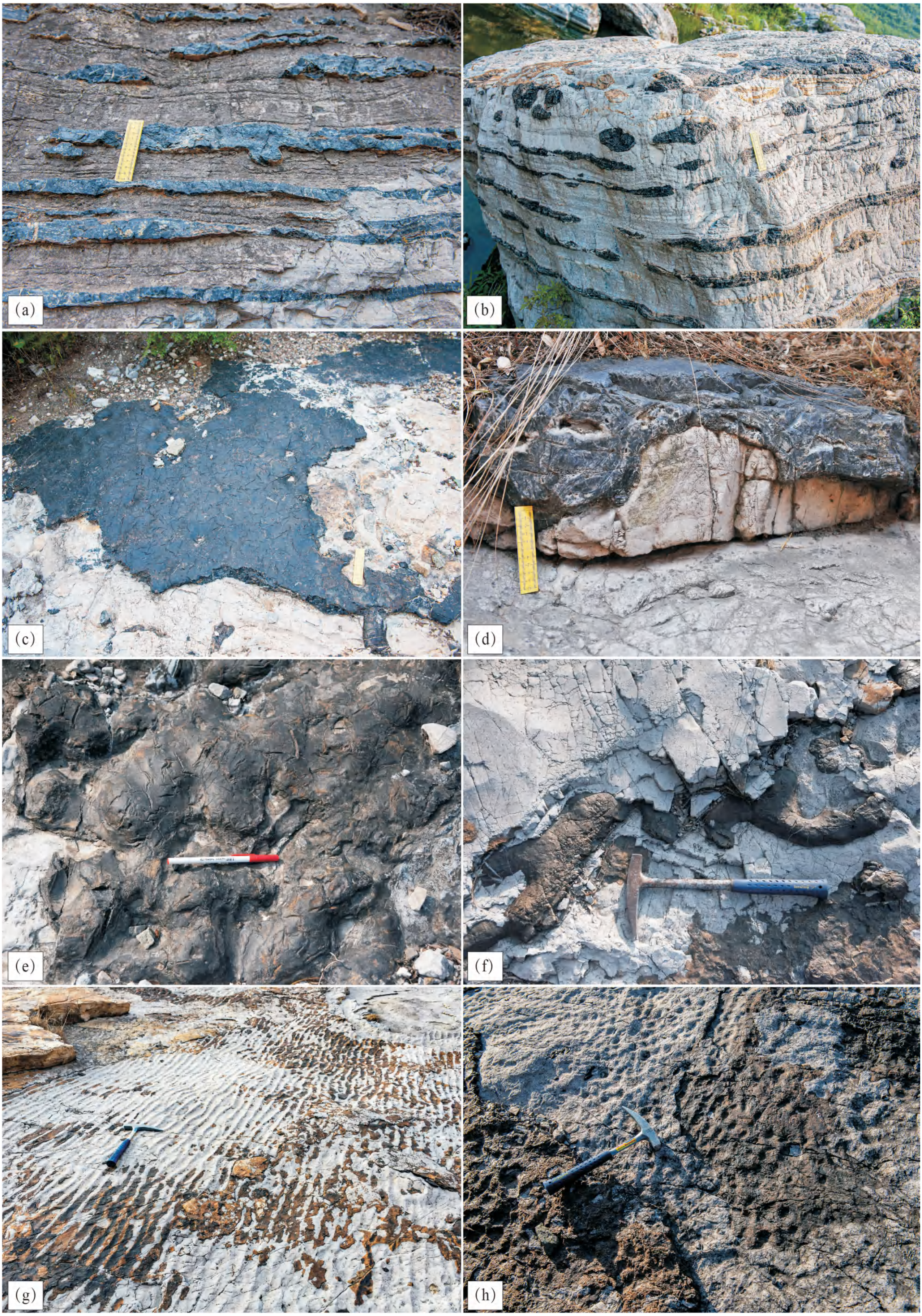

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

图 2 北京西山庄户洼村露头硅质岩产状与其伴生的波痕、干涉波痕:(a) 雾迷山组中常见的硅质条带白云岩(正常风化表面);(b) 雾迷山组中常见的硅质条带白云岩(河水冲刷后新鲜的岩石);(c) 上覆白云岩剥蚀后呈现出的硅质岩;(d) 随着原始起伏层面而沉积的硅质岩,呈现出明显的薄厚变化;(e) 附着在原始层面上的硅质岩,其原始堆积与生物作用有关;(f) 压实、固结之后硅质岩在剖面上呈现断续分布,但在层面上多呈枝状且互相连通,在剖面上显示为底辟构造;(g) 与波痕共生的硅质岩,主要赋存于波谷;(h) 与干涉波痕共生的硅质岩

Fig. 2 Field occurrence of siliceous rock and its associated ripples and interference ripples at Zhuanghuwa Village, Western Hills, Beijing: (a) siliceous strip dolostone commonly found in the Mesoproterozoic Wumishan Formation (normally weathered surface); (b) siliceous strip dolostone commonly found in the Wumishan Formation (fresh rock after river scouring); (c) siliceous rock after the overlying dolostone is denuded; (d) siliceous rock deposited with the original undulating layer, showing obvious changes in thickness; (e) silica attached to the original layer siliceous rock, its original accumulation is related to biological action; (f) siliceous rock is intermittently distributed on the section after compaction and consolidation, but it is mostly branched and connected with each other on the layer, and it is shown as thediapirs on the lateral section; (g) siliceous rock coexisting with standard wave marks, mainly occurring in wave troughs; (h) siliceous rock coexisting with interference wave marks

屑白云岩有两处明显向硅质岩团块内部突进。显然,硅质团块被白云质灰泥包裹时具有一定的塑性,因而被白云质砾屑“侵入”。

还可见到完全包裹在白云岩中的硅质岩团块被拉断,并发生明显变形和错位现象,在拉断的硅质岩团块中间还包裹有边界截然的白云岩砾石(图 3d 红色箭头),白云岩与硅质岩之间没有任何交代、置换的痕迹。

有些成层的硅质岩见有明显的底辟现象(图 3e、f),并且底辟的规模与硅质岩的原始厚度有一定的正相关性。有些覆盖在硅质岩之上的薄层白云岩还出现了被硅质岩向上挤裂的现象(图 3g 红色箭头处)。有些在剖面上呈眼球状的硅质结核,具有多层的同心纹层,以前认为是典型的成岩结核(图 3h①),仔细观察,这种同心层都是原始的硅质岩和白云岩互层变形的产物,从剖面上看好像孤立的同心结核,实际上它的周围还有椭圆形态的硅质结核(图 3h②),再向周围追索,与之相同层位但距离稍远处还有近层状的硅质透镜(图 3h③),它们三者并不是彼此孤立,而是彼此连通(详见后面讨论部分)。

最为典型的是在多个不同层位的硅质岩团块和结核中发现了明显被白云岩脉侵入或切穿的现象(图 4a—d),这种硅质岩被白云岩侵入的现象与笔者等之前发现的白云岩被硅质岩脉侵入的现象(图 5 及 Su Dechen et al., 2014),都在庄户洼剖面,但在不同的层位。这些现象说明:硅质团块包裹在白云质灰泥中虽然尚有一定的塑性,但随着时间的推移而逐渐变脆,当整体受到外来应力时局部发生脆性破裂,于是尚未固结的白云质灰泥贯入裂缝之中形成白云质“砂脉”。

笔者等对 2014 年报道的硅质岩脉侵入到白云岩中的古地震现象又进行了深入观察,在同一地点发现了更多的硅质沉积物向上涌动或流动的痕迹(图 5)。

图 5a 清晰地记录了地震发生时各层位的状态以及硅质沉积物在地震时发生触变流动的轨迹。当时,下部的三层白云岩(Dol①、Dol②和 Dol③)已经基本固结,地震发生时只能产生脆性变形,但上部的白云质灰泥(Dol④)仍处于半固结状态。而介于三层白云质沉积物之间的硅胶(Si①和 Si②)仍处于半固结状态。强烈的地震导致两层硅胶之间已经固结的第 2 层白云岩(Dol②)出现裂隙——地裂缝,与此同时,两层硅质岩(Si①和 Si②)发生触变流动,底层的硅胶(Si①)通过第 2 层白云岩(Dol②)中的裂隙与上部的硅胶层(Si②)汇合后,沿着第 3 层白云岩(Dol③)的裂隙向上穿刺,在第 4 层白云岩(Dol④)中形成两条细脉。最终形成现在这种触变脉(塑性变形)和地裂缝(脆性变形)共存的现象。

3　雾迷山组硅质岩成因讨论

3.1　成因争论史

硅质岩的成因曾经是地质学界争论的热门话题,涉及物源、沉积和成岩整个过程。

燧石性脆质坚,自古就是人类文明的重要原料,也是现代地质科学很早关注的研究对象(例如:Lyell, 1830, 1871)。Woodward(1864)在燧石标本中识别了出明显的海绵结构,认为燧石为生物成因。许多学者则认为,海水中的硅质胶体具有极强的吸附性,不仅彼此之间吸附,还吸附其周边的物质,凝

聚固结而形成燧石，硅质的来源主要为陆源物质的风化溶解（Prestwich，1888；Tarr，1917；Pettijohn，1949；Humphries，1956；Tresise，1961；Hesse，1989）。然而，也有学者通过实验认为，正常温度下海水中溶解的硅质不足以达到无机沉淀的浓度，除非附近有火山活动（Krauskopf，1956）。

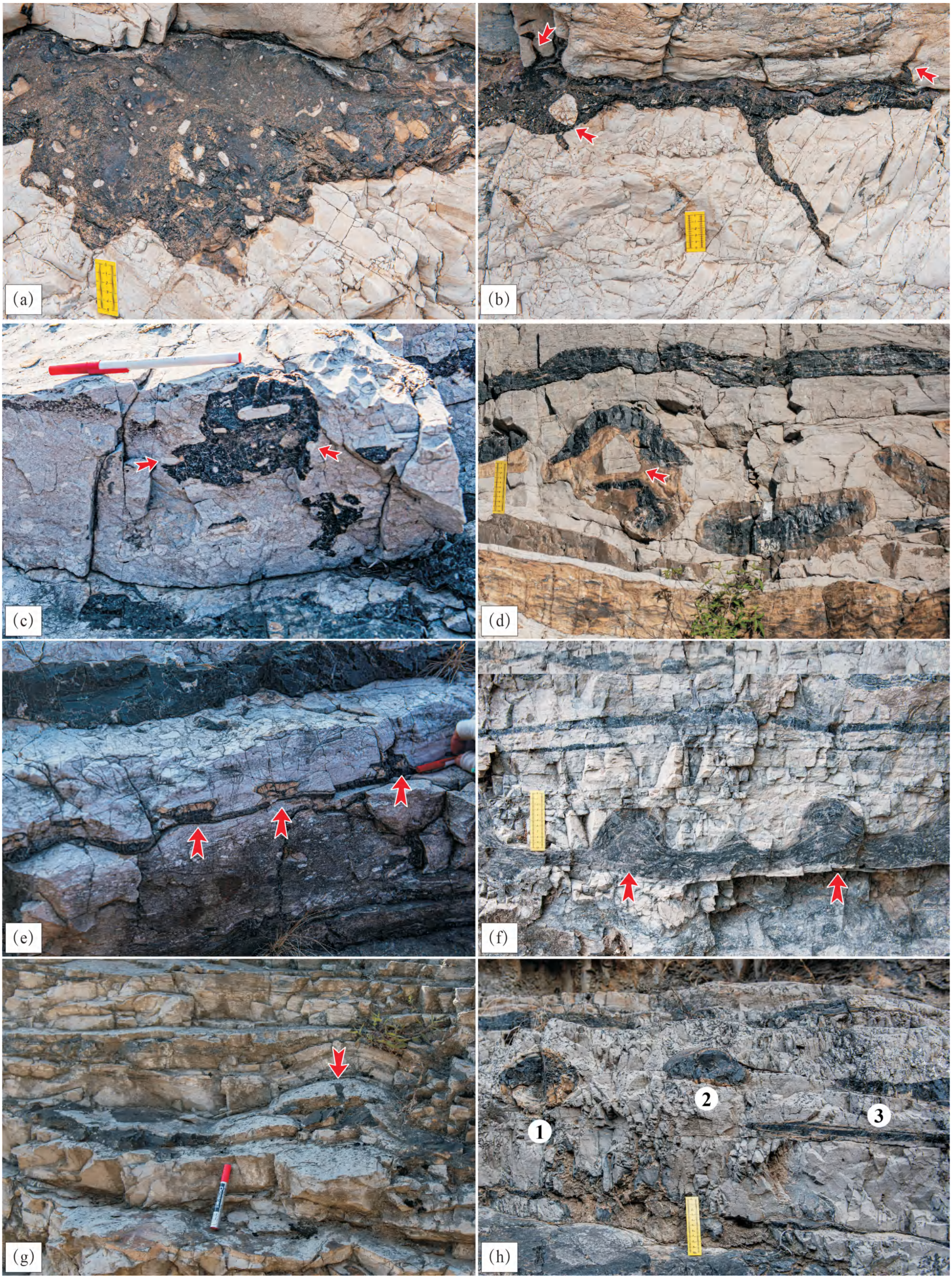


图 3 北京西山庄户洼村露头硅质岩野外产状

Fig. 3 Field occurrence of siliceous rocks at Zhuanghuwa Village, Western Hills, Beijing

(a) 位于沉积间断面上的硅质岩,内部夹杂大量白云质同生角砾,角砾与硅质岩之间界线清晰,二者之间没有交代关系,而是白云岩角砾被硅质胶结而成;(b) 与(a)为同一层位的硅质岩,除其中混有的白云质同生角砾外,注意从剖面上可见硅质岩上、下层位的裂隙均被硅质岩挤入充填,说明硅质岩明显晚于白云岩固结,因而在受到垂向的挤压(重力压实)或地震的震动时,挤入上下层的裂缝中,形成这种挤入构造;(c) 混有白云岩砾屑且未完全固结的硅质团块与大量白云质砾屑、砂屑一起沉积,硅质团块的边界明显,但有被挤压形成的变形特征;(d) 粒度大于 5 cm 的白云岩角砾被硅质团块"捕获",再参与到岩石的沉积成岩过程,相邻多个硅质团块的排列方式显示这些硅质团块彼此之间可能是连续的;(e)、(f) 层状的硅质沉积物受到挤压时向上方挤入,形成底辟构造,但(e)中的底辟构造为上大下小的伞状,(f)中的底辟构造为穹丘状;(g) 硅质沉积物受力向上挤入时,冲破了上覆薄层白云质沉积岩的束缚,白云岩裂开。说明当时硅质沉积物固结速度慢,为软的硅质胶团,而白云质沉积物已经固结,受硅质胶团的挤压后产生明显的脆性变形;(h) 断面呈圆形(①)、椭圆形(②)的硅质团块与层状的硅质沉积物(③)原本为同一层,受力挤压后,①和②形成不同形态的独立的硅质体

(a) Siliceous rock located on the sedimentary discontinuity, with a large number of dolostone breccia mixed in it. The boundary between the breccia and the siliceous rock is clear. (b) Siliceous rock in the same layer as (a), except for the mixed dolostone breccia, it can be seen from the section that the fractures in the upper and lower layers of the siliceous rock are squeezed and filled by the siliceous rock , indicating that the siliceous rock consolidated significantly later than the dolostone, so when subjected to vertical compression (gravity compaction) or earthquake vibration, it squeezed into the cracks of the upper and lower layers to form this squeezed structure. (c) The siliceous agglomerates mixed with dolostone gravel and not fully consolidated are deposited together with a large number of dolostone gravels and sands. The boundary of the siliceous agglomerate is obvious, but it has the characteristics of deformation formed by extrusion. (d) Dolostone breccia with a particle size larger than 5 cm is "captured" by siliceous clumps, and then participates in the sedimentary diagenetic process of the rock. The arrangement of adjacent siliceous clumps shows that these siliceous clumps may be continuous with each other。(e), (f) The layered siliceous sediments are squeezed upward when they are squeezed to form a diapir structure, but the diapir structure in (e) is umbrella-shaped and the diapir structure in (f) is dome-shaped. (g) When the siliceous sediment is pushed upward by force, it breaks through the restraint of the overlying layer of dolostone. This indicates that the siliceous sediments had a slow consolidation speed at that time and were soft siliceous micelles, while the dolomitic deposits had already consolidated and were compressed by the siliceous micelles and had obvious brittle deformation. (h) The shapes of siliceous agglomerates change from the round ① to elliptical ②, and to the layered ③. They were originally from the same layer

1967 年,Eugster 在肯尼亚马加迪湖的湖床中发现了两种新的含水硅酸钠矿物(马加迪石和肯尼亚石),并认为这两种矿物是在碱性盐水中经化学沉淀形成,最终转变为燧石(Eugster,1967; 1969)。然而,Behr 和 Röhricht(2000) 认为,肯尼亚马加迪湖中只有极少的燧石直接源于化学沉淀,大多数燧石不是化学沉淀成因,而是在生物作用的参与下形成的。

20 世纪 70 年代中后期,Folk 等对意大利 4 个中生代盆地的燧石结核、透镜体和燧石层进行了研究,认为这些燧石均为生物成因的硅质交代碳酸盐矿物后所形成(Folk and McBride, 1978; McBride and Folk, 1979)。

20 世纪 80 年代以来,Murray 对不同大地构造环境的燧石进行了较系统的地球化学研究,并于 1994 年对燧石的沉积环境与地球化学特征之间的判别进行了系统的论述。Murray 同时指出,地球化学数据并非判定燧石成因环境的灵丹妙药,更不应该只限于某一种地球化学指标,必须结合全面的地层学和岩石学研究。(Murray,1994)。让 Murray 言中的是,这些以地球化学数据为基础研究的"成果"被效仿者奉为至宝,以至于很多研究舍弃了基本的野外观察、描述和现场分析。

中国大陆广泛分布着从前寒武纪到古生代多个地质时代的碳酸盐岩,很多碳酸盐岩中夹有燧石构成的硅质层、硅质条带或硅质结核,有些时代的碳酸盐岩地层中硅质岩的含量极高。叶连俊(1945)对云南昭通石炭系煤系中的燧石进行了系统研究,认为这些燧石层的硅质来源于陆地岩石风化,在海水中呈胶体形式存在,在合适的条件下发生化学沉积而形成。任磊夫(1959)对湖北荆襄震旦纪地层中的硅质结核进行了详细的野外观察和对比研究,认为这些结核是沉积于海底的硅胶在成岩阶段重新聚集所形成,为无机成因。夏邦栋(1965)对江苏宁镇山脉古生代碳酸盐岩地层中的燧石结核进行了详细观察和研究,发现了在层间的间断时间较短的古侵蚀面和缝合线中存在的两类原生燧石结核,它们都是在上覆碳酸盐物质堆积之前与其周围的沉积物同时形成,其内部常胶结有下伏岩石的砾石,是同沉积的二氧化硅的胶凝体聚集形成。张荫本(1966)则认为,宁镇山脉古生代碳酸盐岩地层中除了有无机成因的燧石外,还有生物成因(有机成因)和生物化

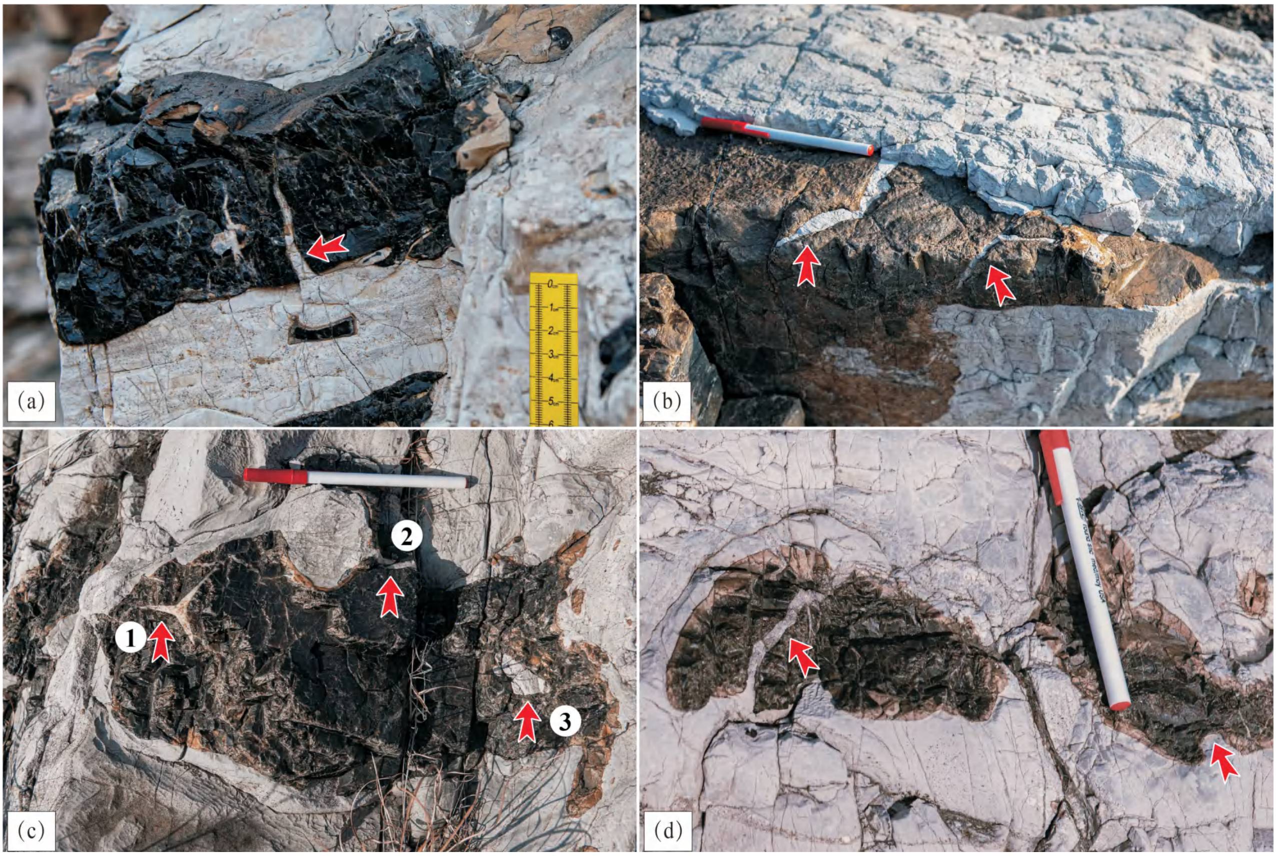


图 4 硅质岩被白云岩穿刺“侵入”的现象

Fig. 4 The phenomenon of “intrusion” of siliceous rock by dolostone

(a) 质地较纯的硅质团块被白云质沉积物穿刺,形成 5 cm 高的白云岩细脉,充分说明穿刺发生时,硅质沉积物与白云质沉积物都是相对软的状态,为同沉积的构造;(b)、(c)、(d) 均为相邻层位不同位置发现的硅质沉积物被白云质沉积物穿刺的现象

(a) The siliceous mass of relatively pure texture was punctured by dolomitic sediments to form 5 cm-high dolostone veinlets, which fully shows that when the puncture occurred, both siliceous and dolomitic sediments were relatively soft and the feature is syndepositional; (b), (c) and (d) are all similar phenomena of siliceous sediments intruded by dolomitic sediments found at different positions in adjacent horizons

学成因的燧石,并给出了四川盆地二叠纪地层的燧石结核中有大量微体动物化石的实例。赵澂林等(1977)对太行山中北段高于庄组—雾迷山组中的燧石成因和硅质来源进行了详细的研究,在雾迷山组硅质岩中发现了沥青质和藻类结构。

张鹏远(1979,1980, 1982)、赵澂林(1980)、朱浩然等(1980)、刘志礼等(1982)和孙淑芬等(2006)分别报道了蓟县和北京西山的雾迷山组燧石中发现了绿藻等微体古生物化石。Ding Tiping 等(2017)发现在高于庄组到雾迷山组的沉积过程中,海水中 δ^{30}Si 值达到了自古元古代以来的峰值,说明在这段时间中海水中溶解的硅浓度急剧下降。这个急剧下降期恰好对应于中元古界中燧石最为发育的阶段。任国选等(2008)和赵悦等(2019)则认为,中元古界中的燧石条带“是一种具有时代特征的同沉积的生物化学沉积”。

具体到雾迷山组,可以归纳为两个主要问题,一是硅质的来源,二是硅质岩的成岩机制。

3.2 硅质来源

部分学者认为中元古界雾迷山组中的硅来源于富硅的热水活动或火山喷发(例如:任国选等,2008),另有学者认为来源于生物(例如:赵悦等,2019)或陆源物质的长期风化。如前所述,雾迷山组分布面积巨大,有大量的硅质岩,如果这些硅质来源于火山活动,那么,雾迷山组中应该有大量的火山活动遗迹。而事实上,整个华北地区中—新元古代的火山活动遗迹主要见于大红峪组和团山子组,其中,大红峪组中的火山岩分布面积达到 600 km^2,在北京平谷区的最大厚度达到 718 m(和政军等,2000b)。在其他各组如高于庄组、雾迷山组、杨庄

组、铁岭组和下马岭组中都很少见到火山产物,这也是包括雾迷山组在内的中元古代地层直到最近十余年才找到极少量的凝灰岩测年样品的原因(李怀坤等,2014;高林志等,2007,2011;Su Wenbo et al.,2010;Su Wenbo, 2016)。在常州沟组沉积之前,华北已经经历了数亿年的风化剥蚀,中元古代的海洋中虽然沉积了上千米厚的石英砂岩,但一定有足够多的硅质溶于海水中,这些硅质更可能是高于庄组和雾迷山组中硅质岩的重要来源。

地震液化溢出丘的围岩是庄户洼附近最典型的岩石(图 6a),镜下研究发现,岩石主要为含有石英砂屑和残余菌藻的亮晶白云岩,白云石总含量 93%,以砂屑和胶结物两种形式存在。岩石中含有以石英颗粒为主的陆源组分,石英含量 5%,为次圆状,粒径 0.1~0.3 mm,可见残留加大边,个别石英碎屑内含有电气石矿物包裹体,分布不均匀,局部相对富集(图 6b)。

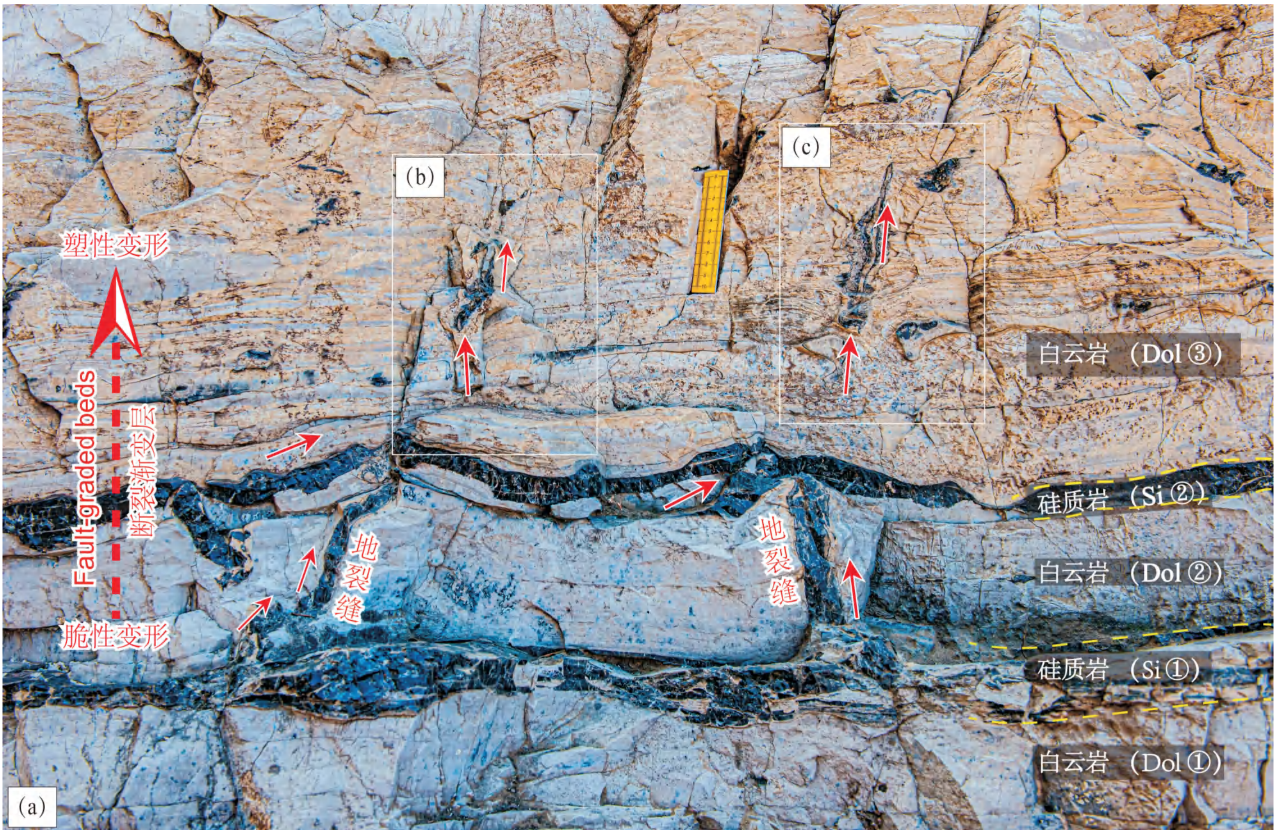
溢出丘顶部的黑色的硅质岩中,隐晶质石英 90%以上,有少量放射球粒状玉髓;硅质岩中有 10%左右的粒状藻鲕,直径约为 0.2 mm,以同心状为主,个别呈放射状(图 6c,图 6d),放射状的藻鲕很可能是原始的生命结构,这种质地比较纯的硅质岩在形成过程中,有生物作用的参与。

根据雾迷山组中大量叠层石、薄片中同心状硅质藻鲕和放射状硅质藻丝的存在(图 6),说明雾迷山组中的硅质岩的形成在一定程度上受到生物活动影响,析出后的聚集过程则主要受海洋的物理化学条件和生物作用共同控制,而发生选择性的聚集和沉淀。

笔者等在此强调的是:无论是从海水中直接沉淀或是微生物介导聚集,这些硅质沉积物在白云岩灰泥表面堆积时为典型的硅胶软团,与海水之间有明显的相变界面,以硅胶形式凝聚在海底直到最终固化成岩阶段,与白云质灰泥(碳酸盐碎屑)一起经历了机械沉积作用以及相应的软沉积物变形作用。在特殊的外力作用下(例如地震、海啸的振荡作用甚至正常的重力压实作用),未固结的硅胶团块会发生聚集变形形成底辟构造、或以硅质脉的形式侵入到其外围未固结沉积物中。因此,这些硅质岩从凝聚在海底开始到最终固结成岩,最主要的变化就是硅胶固化作用,而影响其固化的主要因素就是时间。

3.3　硅质岩的形成过程

大量的野外实地观察证明,至少雾迷山组中绝大多数暗色条带状、结核状、团块状的硅质岩为原生成因,而非后期交代成因。那些因古地震而刺穿白云岩的硅质液化脉以及被白云岩细脉刺穿的硅质岩



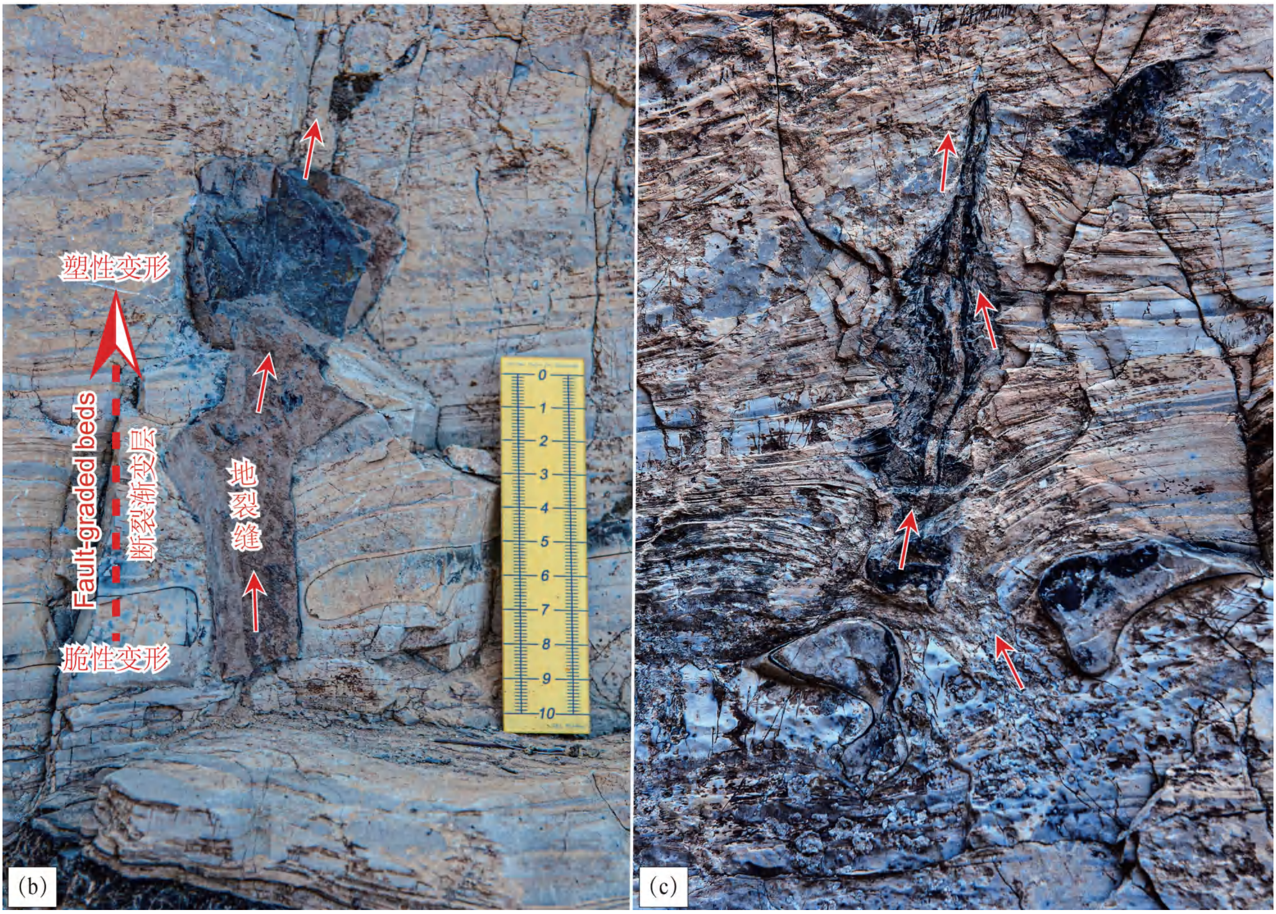


图 5 白云岩中的硅质岩脉

Fig. 5 The siliceous dikes in dolostone

(a) 总厚 70 cm 的岩石剖面自下而上分为 6 层，其中 Dol①、Dol②、Dol③和 Dol④主要为白云岩，Dol③和 Dol④之间是渐变过渡关系。Si①和 Si②则以硅质岩为主，Si①中包含极薄的白云岩纹层，Si②则由较纯的燧石构成。(b)、(c) 古地震发生时，下部固结速度快的白云质沉积物呈脆性裂开，固结速度慢的硅质沉积物在地震的作用下向压力小的上方运移，即硅①和硅②中的硅质沉积物向上侵入到尚未固结的液化后的硅质沉积物穿刺到未固结的白云质沉积物(Dol③和 Dol④)中，形成硅质岩脉

(a) The rock profile with a total thickness of 70 cm is divided into 6 layers from bottom to top, 4 layers of dolomite (Dol① to Dol④) and 2 layers of chert(Si① and Si②). (b), (c) When the paleo-earthquake occurred, the dolomitic sediments with fast consolidation speed in the lower part were brittle and cracked, and the siliceous sediments with slow consolidation speed migrated to the upper part of the lower pressure under the action of the earthquake, that is, the siliceous sediments in Si① and Si ② are intruded upwards into the unconsolidated liquefied siliceous deposits punctured into the unconsolidated dolomitic deposits (Dol ③ and Dol④) to form siliceous dykes

无可争辩地证明，雾迷山组中主要的硅质沉积物为原生成因。原生的硅质岩中又可进一步分为生物吸附聚集和和硅胶凝聚堆积。生物成因为原生的藻叠层石吸附聚集和鲕粒吸附聚集，主要表现为硅质的纹层状结构。硅胶凝聚团块堆积的硅质岩主要表现为各种形态的硅质岩透镜体、薄饼、薄层等，这种形态的硅质岩占主导地位，在二维的剖面上表现为硅质结核或条带。

硅质胶体因遵循能量最低原理及自重而在白云质灰泥表面的低洼处聚集成透镜体或席状体(图 7a、b)，继而呈层状覆盖在白云质灰泥之上(图 7c)。其上再被后来的白云质灰泥、碎屑所覆盖，在重力作用下，硅质胶团经常表现为大小不等的片状分布，而二维的剖面上则表现为硅质层、硅质条带和硅质结核(图 7d)。硅胶席在完全固结前，容易因地震等外力作用而发生变形。

极浅水的碳酸盐台地常常遭受风暴和大浪袭击，因此白云质灰泥、碎屑反复搬运、再聚集，半固结状态的硅胶可以被打碎并裹挟到白云质灰泥中二次搬运，因此事件沉积灰泥层内不仅有大小不等的白

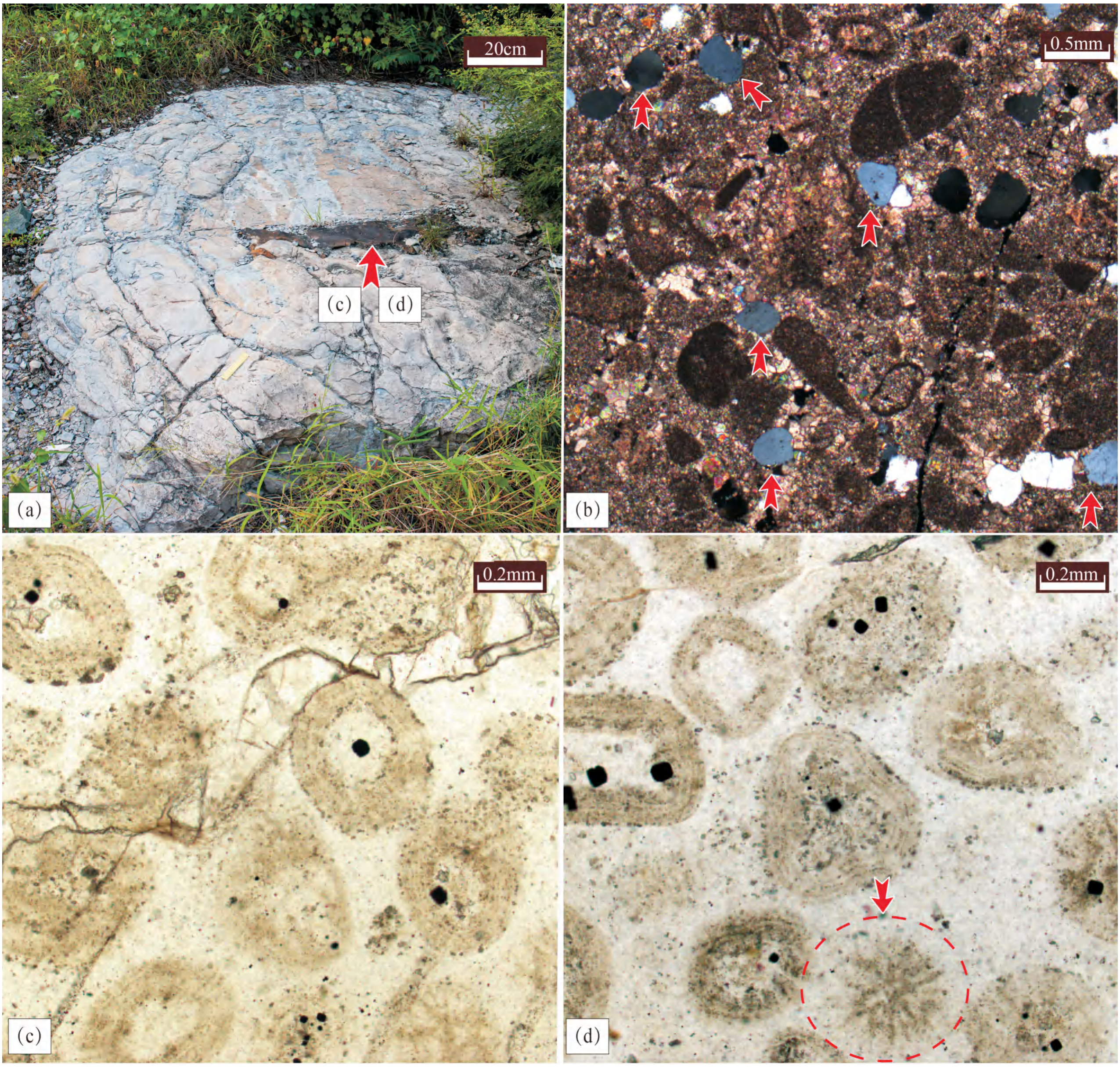


图 6 北京西山庄户洼村雾迷山组硅质白云岩、硅质岩的显微特征

Fig. 6 Microscopic characteristics of siliceous dolostone and siliceous rock at the Zhuanghuwa Village of the Western Hills of Beijing

(a) 雾迷山组中含石英碎屑和鲕粒的白云质沉积物在地震时液化并喷出形成的液化溢出丘(Su Dechen et al., 2014),丘顶凹陷处(红色箭头)以及丘体内产生的环形和放射状裂隙被之后沉淀的暗色硅质软泥充填;(b) 白云岩中的石英碎屑(正交偏光);(c) 硅质岩中的藻鲕(单偏光);(d) 白云岩中的硅质鲕粒和藻丝(红色箭头)(单偏光)

(a) The seismic-triggered liquefication mound (Su Dechen et al., 2014) is composed mainly by dolomitic sediments with some quartz debris and oolites in the Wumishan Formation. The fissures are filled with later deposited dark siliceous ooze. (b) Quartz clasts in dolostone (cross-polarized light); (c) Algal oolites in siliceous rock (single-polarized light); (d) Siliceous oolites and algal filaments (red arrow) in dolostone (single polarized light)

云石角砾或磨圆的砾石,也可见变形的燧石团块和燧石角砾等。

3.4　硅胶固化后经受改造的硅质岩

雾迷山组中确实有部分硅质岩在成岩之后发生改造变化,即在原生的硅质条带基础上发生重结晶,原生的暗色条带变成质地纯净的浅色燧石甚至是石英,但原始的硅质岩的结构和产状依然保留(图 8a,图 8c②),呈层状或纹层状产出。重结晶作用的热

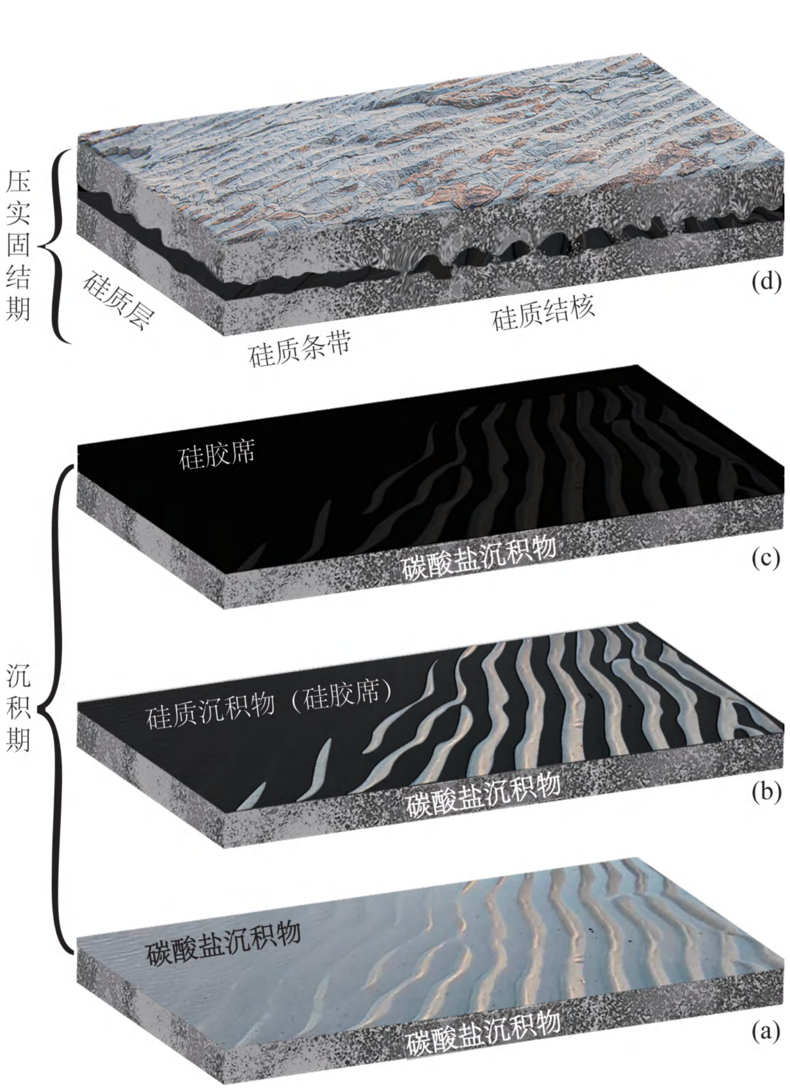


图 7 雾迷山组中的硅质岩形成模式：(a)—(c) 硅胶席的形成过程；(d)硅胶席在成岩期间经差异压实或外力而变形，最终固结成燧石结核、燧石条带或燧石层

Fig. 7 Formation model of siliceous rocks in the Mesoproterozoic Wumishan Formation: (a) (c) the formation process of the silica gel mat; (d) during diagenesis, the silica gel mat was deformed by differential compaction or external forces, and finally consolidated into chert nodules, chert strips or chert layers

源与区域上印支期岩浆活动有直接关系，只不过这里的岩浆活动强度较小，白云岩没有变为白云质大理岩。

还有一种硅质岩质地极纯，沿着成岩后的裂隙发育，不受层理或层面控制，是含二氧化硅的溶液沿着后期构造作用形成的空间沉淀生成(图 8b，图 8c③))，明显受构造作用控制。此类硅质岩含量极少。

3.5 硅质的来源及海洋物理化学环境

本文仅从燧石结核(条带)、硅质席与白云岩的关系及沉积结构构造特征，证明燧石结核、燧石层或燧石条带等是由浅水中的硅胶席固化而成，是沉积原生的而不是成岩后生的，生物作用是次要的。而构成硅胶的硅质来源，尚不清楚，可能有陆源搬运而来，也可能有海底热水带来。

依本文证据可以确认，中元古界雾迷山组沉积时，海底同时存在原生的白云石砂和硅质胶体，这样的海水物理化学条件似乎比较苛刻，尚需进一步研究。

4 结论

通过对北京西山中元古代雾迷山组白云岩及燧石条带进行的野外观察和薄片研究，笔者等得到结论如下：

(1)燧石“结核”并非结核，而是硅胶席经过压实固化的结果。雾迷山组中的白云岩主要为白云质碎屑和灰泥的机械堆积和藻类粘结成因，白云岩与硅胶席之间长期反复相互覆盖，构成了雾迷山组巨厚的硅质白云岩建造。

(2)硅质条带、硅质团块或硅质层与白云岩之间的界线清晰。硅质沉积物聚集的部位或层位最常发育于白云岩层面面上，尤其是有较强侵蚀作用的间断面上，硅质体内部常有大小不等但边界明显的白云质砾屑。

(3)白云质碎屑和灰泥的胶结速度明显快于硅胶席的固化速度，当上覆白云质灰泥已经弱固结时，其下的硅胶团块仍然保持一定程度的塑性或流动性。所以，当地震发生时，或上覆沉积物厚度过大时，软的硅胶层沿着半固结的白云质灰泥层中的裂隙向上侵入或向下方的裂隙挤入，形成多种软沉积物变形构造。

(4)硅胶固化作用是北京西山庄户洼地区中元古界雾迷山组中原生燧石的唯一成因。其他地区其他时代的含硅质条带的碳酸盐岩应当可能有相似的形成过程。

(5)本文证据表明，在中元古代雾迷山组沉积时期，海水中存在大量硅质和碳酸镁，因而可以直接形成硅胶席和白云质灰泥和砂屑、砾屑等，现代海洋环境不具备这样的条件。对于雾迷山期的海洋环境，如离子浓度、pH、Eh 等，尚需进一步研究。

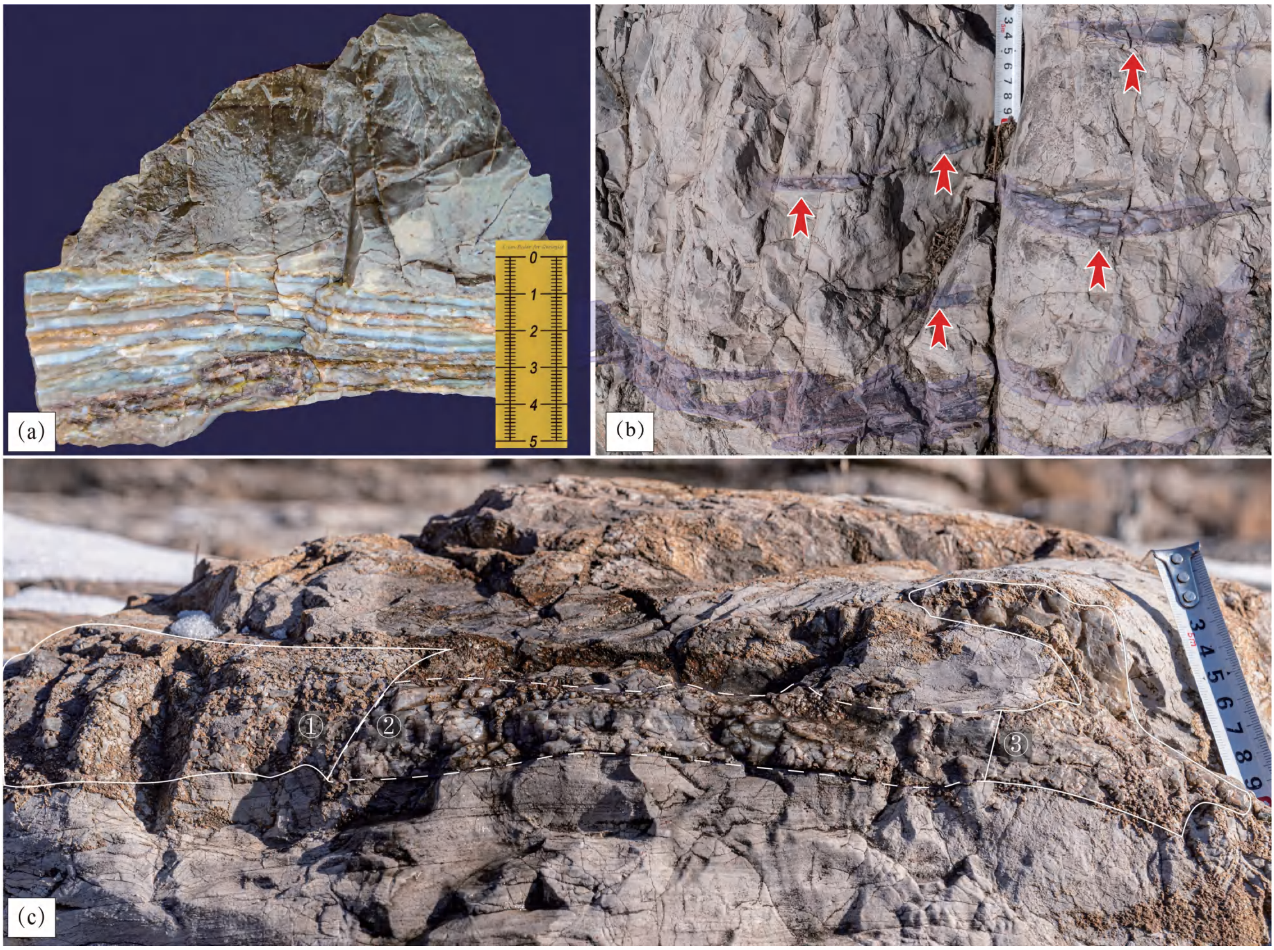


图 8 成岩后重结晶的硅质岩(a) 和后期热液硅质脉体(b)

Fig. 8 Re-crystallized siliceous rocks after diagenesis (a) and hydrothermal siliceous dykes(b)

(a) 雾迷山组中常见的浅色、质纯硅质条带白云岩(标本采自北京延庆区);(b) 白云岩裂隙中充填的纯石英构成的硅质岩;(c) 三种不同形式的硅质岩共生:① 碎裂的硅质颗粒重新胶结形成的硅质岩;② 仍保留原始藻纹层的硅质岩;③ 沿裂隙产出的质地很纯的石英岩,并与原始的硅质条带呈过渡关系,说明裂隙中的硅质可能来源于原始的硅质条带白云岩

(a) The common light-colored and pure siliceous banded dolostone in the Wumishan Formation (specimen is collected from Yanqing District, Beijing). (b) Siliceous rock composed of pure quartz filled in dolostone fissures. (c) Three different forms of siliceous rock symbiosis: ① siliceous rock formed by re-cementation of fragmented siliceous particles; ② siliceous rock that still retains the original algal laminae; ③ the pure quartz produced along the fracture. It is in a transitional relationship with the original siliceous strip, indicating that the siliceous in the fractures is probably derived from the original siliceous banded dolostone

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An arguement on origin of chert bands in carbonate rocks
——A case study of the Mesoproterozoic Wumishan Formation in the Western Hills of Beijing

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Abstract: The Mesoproterozoic Wumishan Formation in Beijing area is mainly composed of chert banded dolostone, chert nodule dolostone, stromatolite dolostone and a small amount of terrigenous silty clastic dolostone. It is widely exposed in the Beijing mountain area with a thickness of 2000～3500 meters. The provenance and cause of the formation of a large number of Mesoproterozoic siliceous sediments represented by the Wumishan Formation have been a controversial issue in the geoscience field for a long time. Most researchers believe that layered chert is biogenic and nodular chert is the diagenetic replacement. After detailed field investigations in the Western Hills of Beijing and other places, the authors have found that most of the siliceous bands or siliceous nodules (generally referred to as chert mat or siliceous gel mat in the following) occur on the sedimentary discontinuity surface, especially on the ancient erosion surface. The underlying dolostone gravels are often cemented with the siliceous material. The interior of chert mats is often mixed with impurities, especially organic matter, showing various dark and mottled colors. Chert mats were formed at the same time with surrounding dolomitic debris before the accumulation of the overlying dolomitic sediments. There is a relationship of mutual interpenetration and wrapping between chert mats and dolomitic sediments, but the boundaries between them are clear. Neither dolostone debris nor chert mat has obvious replacement trace. Therefore, the author believes that the "concretion" of chert is the result of silica gel aggregation and solidification. Silica gel solidification is the only genetic mechanism of primary chert in Wumishan Formation. Usually, the cementation rate of dolomitic mud and intraclast is obviously faster than that of silica gel mat. When an earthquake occurs or the overlying sediment is too thick, the soft silica gel will intrude upward or squeeze downward along the weakly consolidated dolostone fissure to form siliceous dykes. In the event of later magma intrusion or transformation by thermal metamorphism, the composition and color of chert strips and chert concretions will change accordingly. The texture becomes pure, and the color changes from dark to light, but the original bedding or texture is still retained, which is easily mistaken for diagenetic or post-diagenetic siliceous replacement of carbonate minerals.

Keywords: chert strip; chert nodule; dolostone; silica gel mat; semi-consolidation; replacement

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