https://doi.org/10.3799/dqkx.2018.107

朝鲜平南盆地寒武系黄州群和法洞群的碳同位素漂移事件

金明哲[1,2],杨正赫[1,2],彭 澎[2,3*],张志越[2,3],朴贤旭[1],
卞创男[4],朴 雄[1],郑哲寿[1],翟明国[2,3]

1.朝鲜国家科学院地质学研究所,朝鲜平壤 3812100
2.中国科学院地质与地球物理研究所,北京 100029
3.中国科学院大学,北京 100049
4.平城煤工业大学,朝鲜平城 999093

摘要: 朝鲜平南盆地寒武系包括黄州群和法洞群下部.为了与邻区及世界其他地区同时期地层进行对比,对黄州群(从下到上分为坪山组、中和组、黑桥组和林村组)和法洞群下部(戊辰组和古丰组)进行了生物地层学和碳酸盐岩碳和氧同位素分析.生物地层学研究表明,坪山组和中和组分别不早于寒武系第三阶和第四阶.坪山组 $\delta^{13}C$ 值变化范围为 0~－3.1‰,中和组为－4.7‰~2.0‰,黑桥组为－1.0‰~2.4‰,林村组为－2.6‰~0.4‰,戊辰组为－1.3‰~0.4‰,古丰组为－1.0‰~2.4‰.综合对比分析,坪山组、中和组和黑桥组大致对应寒武系第三阶－第四阶,林村组大致对应第二统与苗岭统界线附近,古丰组大致对应芙蓉统.中和组上部－黑桥组(正漂移)、林村组下部(负漂移)和古丰组中部(正漂移)记录的3个碳同位素漂移事件可能分别对应 MICE(mIngxinsi carbon isotope excursion)、ROECE(redlichiid-olenellid extinction carbon isotope excursion)和 SPICE(steptoean positive carbon isotope excursion)全球性事件.

关键词: 华北克拉通;朝鲜半岛;平南盆地;寒武系;碳同位素漂移;生物地层学.

中图分类号: P539.7; P56; P534.4 **文章编号:** 1000－2383(2018)11－4096－13 **收稿日期:** 2018－05－23

Carbon Isotope Excursions of Cambrian Hwangju and Bopdong Groups in Pyongnam Basin, Korean Peninsula

Kim Myong-Chol[1,2], Yang Jong-Hyok[1,2], Peng Peng[2,3*], Zhang Zhiyue[2,3], Park Hyon-Uk[1], Byon Chang-Nam[4], Park Ung[1], Jong Chol-Su[1], Zhai Mingguo[2,3]

1.*Institute of Geology, State Academy of Sciences, Pyongyang* 3812100, *DPR Korea*
2.*Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing* 100029, *China*
3.*University of Chinese Academy of Sciences, Beijing* 100049, *China*
4.*University of Pyongsong Coal Industry, Pyongsong* 999093, *DPR Korea*

Abstract: The Cambrian strata in the Pyongnam basin in Korea include the Hwangju Group and the lower Bopdong Group. To compare the Cambrian strata of this basin with those in the adjacent regions and areas beyond, this paper performs biostratigraphy research and isotope analysis of carbon and oxygen isotopes of typical carbonates of the Hwangju Group (the Pyongsan, Junghwa, Hukgyo and Rimchon Fms.) and the lower Bopdong Group (the Mujin and Kopung Fms.). Based on biostratigraphic

基金项目:国家自然科学基金项目(Nos.41772192,41322018);中国科学院前沿重大基础项目(No.QYZDB-SSW-DQC04281712250).
作者简介:金明哲(1967—),男,研究员,地层学专业.
*通讯作者:彭澎,ORCID: 0000-0002-6743-4669. E-mail: pengpengwj@mail.iggcas.ac.cn

引用格式:金明哲,杨正赫,彭澎,等,2018.朝鲜平南盆地寒武系黄州群和法洞群的碳同位素漂移事件.地球科学,43(11): 4096－4108.

research, the Pyongsan and Junghua Formations should be no lower than Stage 3 and Stage 4, respectively. $\delta^{13}C$ values in the Pyongsan Fm. range from 0 to −3.1‰, Junghua −4.7‰ to 2.0‰, Hukgyo −1.0‰ to 2.4‰, Rimchon −2.6‰ to 0.4‰, Mujin −1.3‰ to 0.4‰, and Kopung −1.0‰ to 2.4‰. Synthetically, it is argued that the Pyongsan, Junghua and Hukgyo Fms. belong to Stages 3−4 of Cambrian, the Rimchon Fm. is around the boundary of Series 2 and Miaoling Series, and the Kopung Fm. belongs to the Furong Series of Cambrian. And the three carbon excursions in the upper Junghwa-Hukgyo Fm. (positive), the lower Rimchon Fm. (negative) and the middle Kopung Fm. (positive) are comparable to the global events of the mIngxinsi carbon isotope excursion, redlichiid-olenellid extinction carbon isotope excursion and steptoean positive carbon isotope excursion, respectively.

Key words: North China craton; Korean Peninsula; Pyongnam basin; Cambrian; carbon isotope excursion; biostratigraphy.

0　引言

海相碳酸盐岩的碳同位素组成可以近似地反映同时期海洋中无机碳的组成(Emrich *et al*., 1970; Scholle and Arthur, 1980).前寒武纪“雪球地球”事件(Kirschvink, 1992; Hoffman *et al*., 1998)、二叠纪末和三叠纪末生物的大灭绝(Krull *et al*., 2000; Berner, 2002)等都记录了碳同位素的显著变化.碳同位素地层学成为地层对比和划分的重要手段(Saltzman *et al*., 1998; Zhu *et al*., 2006;樊茹等,2011).寒武纪曾经出现多次碳同位素漂移,包括目前所知显生宙最大碳同位素漂移,其成因可能与寒武纪生命大爆发及环境演变有关(Saltzman *et al*., 1998; Zhu *et al*., 2006;樊茹等,2011).近年来,中国寒武系年代地层序列和生物地层序列的研究取得了进展(彭善池,2009a, 2009b, 2014),获得一系列具有全球对比意义的 $\delta^{13}C$ 漂移事件,建立了碳同位素异常与生物演化之间的关联(Zhu *et al*., 2006, 2007).Zhu *et al*.(2006)根据寒武系地层 $\delta^{13}C$ 变化曲线,指出该时期存在 10 个具有全球对比意义的碳同位素漂移事件,反映主要的生物事件、海平面变化和化石保存之间的关系.

平南盆地位于朝鲜半岛的中部(图 1),广泛发育寒武系地层,碳同位素地层学的研究几乎是个空白.金明哲等(2016)最近对平南盆地黄州群下部层位及燕滩群的碳同位素进行了初步研究,并提出燕滩群对应埃迪卡拉系.本文将进一步分析平南盆地寒武系碳酸盐岩碳同位素演化特征,并与邻区及世界同期地层进行对比,探讨这些变化所代表的事件含义.

1　地质背景

平南盆地是朝鲜半岛寒武系的典型发育区,也是朝鲜半岛地层最齐全、最发育的地区(Kwon *et al*., 2010),盆地北以青川江断裂和昌城−云山断裂为界,与狼林陆块相邻,南与临津江构造带相邻(Ri *et al*., 2010)(图 1).平南盆地南部,寒武系(假)整合在新元古界燕滩群棱里组之上,被奥陶系神谷组(假)整合覆盖.平南盆地北部,寒武系大多与下伏前寒武系不整合,局部(假)整合在棱里组之上(Park, 2012).

寒武系地层包括黄州群(从下至上为坪山组、中和组、黑桥组和林村组)和法洞群下部(戊辰组和古丰组)(Kwon *et al*., 2010).坪山组为海退阶段沉积物,只分布于当时的海洋残留区,分布于平南盆地南部.主要由含磷粉砂岩、碳质板岩、结核状磷块岩和白云岩组成;厚度一般为 20～40 m,有时薄至数米以下.中和组代表新一轮海侵阶段的沉积物,分布于朝鲜半岛各个地区;主要由粉砂岩、钙质粉砂岩、板岩和灰岩组成;盆地南部厚度一般为 300～600 m,部分地区 12～190 m,北部厚度一般为 350～450 m、最厚 589 m.黑桥组主要由细粒砂岩、粉砂岩、板岩和灰岩组成;盆地南部厚度一般为 115～318 m,北部厚度一般为 70～250 m,最厚 340 m.林村组主要由黑色千枚岩类组成,最下部或其间有灰岩的夹层;该组地层沿走向分布稳定,常被当作区域性标志层;盆地南部厚度一般为 10～60 m,部分地区为85～93 m,北部一般为 30～50 m,最薄 4 m、最厚70 m.戊辰组主要由粘土质灰岩、含锰灰岩、层状灰岩组成;南部地区厚度一般为 150～490 m,最厚900 m,北部地区一般为 120～300 m,最厚 400 m.古丰组主要由两层白云岩和两层灰岩互层或一层白云岩和灰岩互层组成.南部地区厚度一般为 400～680 m;北部地区一般为 140～360 m,最厚 650 m.

2　生物地层学

黄州群和法洞群含有大量三叶虫类(Kim, 1978, 1982)、牙形石类(Jong *et al*., 2001; Jong

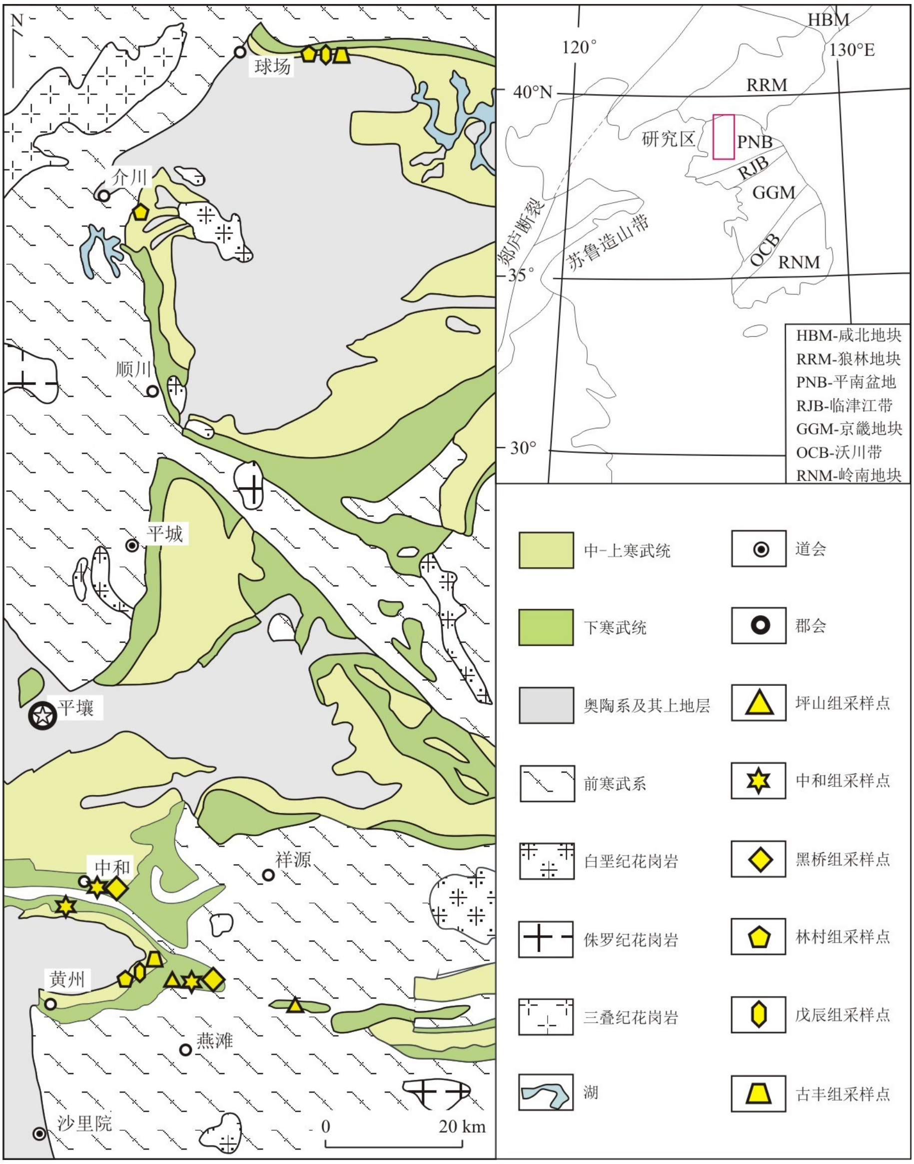

图1 平南盆地中部地质简图

Fig.1 Simplified geological map of the central Pyongnam basin

改编自Paek *et al*.(1996)

and Won, 2002; Won, 2003, 2007; Won and Kim, 2005; Ri *et al*., 2009)、腕足类(Kim, 1988)、海螺类、古杯类、海绵类等动物化石与藻类等植物化石(Paek *et al*., 1996; Kwon *et al*., 2010; Park, 2012)(图2,图3).

坪山组底部是含软舌螺类 *Hyolithes* 和海绵类 *Protospongia* 的含磷粉砂岩,含有少量火山岩.三叶虫类 *Hsuaspis coreanicus* 带位于礼城层灰色板岩或赤色粉砂岩中.礼城层灰岩含有藻类 *Girvanella manchurica* 带,也含有古杯类 *Archaeocyatus* sp.等.中和组底部黄绿色板岩中含有三叶虫类 *Redlichia chinensis* 和腕足类 *Obolus detritus*, *Obolella lunaris*, *Acrotreta coreanica*.在这化石带之上有 *Redlichia nobilis* 带、*Redlichia coreanica* 带、*Redlichia songsinensis* 带、*Redlichia saitoi* 带、*Coreospira rugosa* 带,之后 *Redlichia* 大部分消失,出现新的生物群(Kwon *et al*., 2010).中和组最上部层位的钙质粉砂岩含有 *Kootenia longiformis* 带.含有三叶虫类 *Hsuaspis coreanicus*(图2a),腕足类 *Obolus margaritae*(图2c), *Lingulella manchuriensis*.

黑桥组底部含有 *Oryctocephalus*-*Proliostracus* 带,在这个化石带中含有大量三叶虫类 *Oryctocephalus longispinformis*(图2b), *O. kobagashi*,

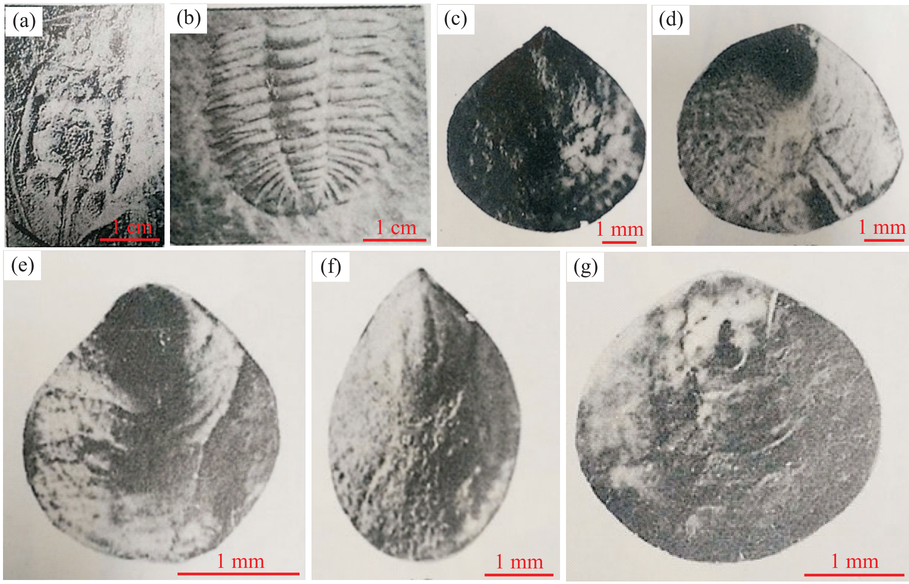

图 2　平南盆地寒武系地层代表性三叶虫(a～b)和腕足类(c～g)化石照片

Fig.2　Representative fossils in the strata of the Cambrian in the Pyongnam basin

a.*Hsuaspis coreanicus*(中和组);b.*Oryctocephalus longispinformis*(黑桥组);c.*Obolus margaritae*(中和组);d.*Botsfordia granulata*(黑桥组);e.*Obolus linyuensis*(戊辰组);f.*Lingulella tangshihensis*(戊辰组);g.*Acrothele asiatica*(戊辰组).参见 Paek *et al*.(1996)

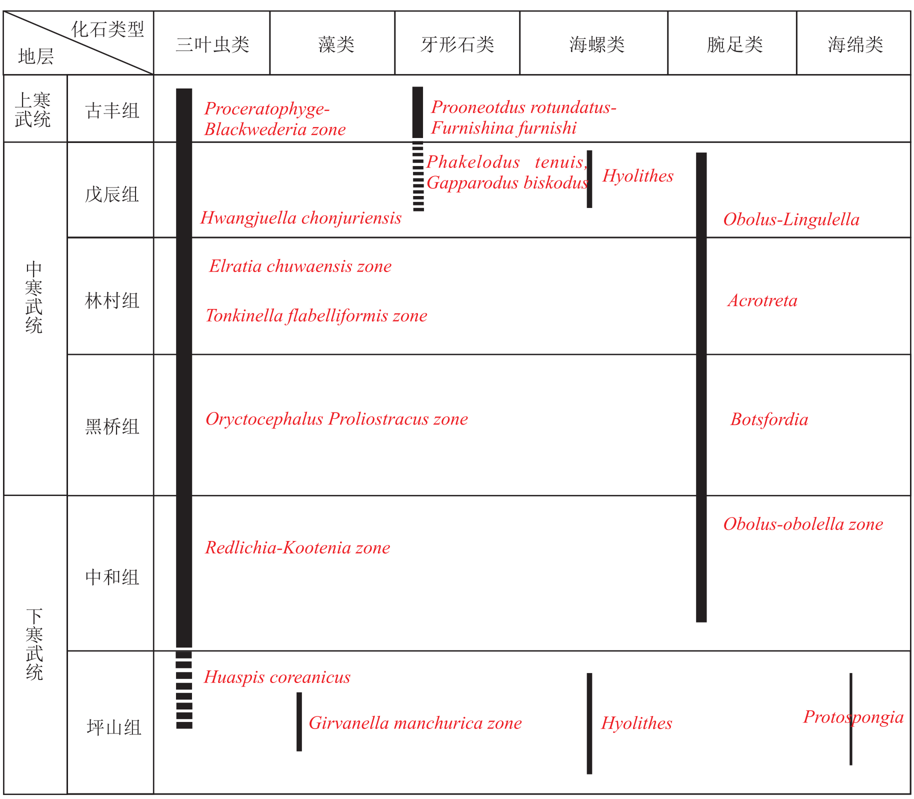

图 3　平南盆地寒武系生物带分布简图

Fig.3　Simplified biozone distribution in the Pyongnam basin during Cambrian period

Oryctocara spinger 等化石.在这化石带之上有 *Pianaspis kodairai* 带、*Okrobonnia chunghwanica* 带.在灰黑色页岩和泥质页岩中发现腕足类 *Botsfordia granulata*(图 2d),*Lingulella* cf. *exilis*.

林村组底部灰紫色灰岩中含有 *Tonkinella flabelliformis* 带,之上的黑色板岩存在 *Elratia chu-*

waensis 带.在灰岩夹层中含有大量三叶虫类 *Tonkinella flobelliformis*，*T. kobayashi*，*T. optura kannoriensis*，sp.，*Szeaspis kannoriensis*，*Elratia chuwaensis*，*Kannoriella chunghwaensis*，*Dorypyge manchuriensis*，*Fuchouia manchunriensis*，*Amecephalus piochensis*，*Chunghwaella coreanica*，*C. okrobonia* 等和腕足类 *Acrotreta* 化石.

戊辰组主要由粘土质灰岩、含锰灰岩和层状灰岩组成.含锰灰岩中存在 *Hwangjuella* 带，在这个化石带中发现了牙形石 *Phakelodus tenuis*，*Gapparodus biskodus* 等(Jong and Won, 2002).含有三叶虫类 *Hwangjuella chonjuriensis*，*Goniagnostus chosensis*，*Hypagnostus hwangjuensis*，*Duamsanella hwanghaiensis*，*Damesopsrien* 等，牙形石类 *Phakelodus tenuis*，*Gapparodus biskodus* 等和腕足类 *Obolus linyuensis*(图2e)，*Obolus matinalis*，*Obolus luanhsiensis*，*Obolus minimus*，*Obolus mollisonensis*，*Obolus obscurus*，*Lingulella tangshihensis*(图2f)，*Lingulella shansiensis*，*Paterina lucina*，*Homotreta shantungesis*，*Homotreta lisani*，*Acrothele asiatica*(图2g)等很多化石.

古丰组含有三叶虫类 *Proceratophyge cylindrica*，*P. ensanensis*，*P.*sp.和 *Blackwelderia* sp.化石与牙形石化石，牙形石为 *Prooneotdus rotundatus-Furnishina furnishi* 群落；下部层位主要含有 *Prooneotodus proconodontus*，*Furnishins*，*Westergaardordina*，*Cambroistodus*，*Fryxellodontus* 等，最上部层位含有 *Tridontus nakamurai*，*Cordylodus proarus*.部分生物带分布见图3.

3 样品与分析方法

从平南盆地寒武系中一共采集了37件碳酸盐岩样品，进行碳与氧同位素测试(表1).采样时尽量选择没有风化的新鲜岩石，避开后期岩脉及含胶结物、混染物部分.提取5～10 g岩石样品，无污染粉碎至200目左右.样品粉末在25 ℃与100% H_3PO_4 进行反应(灰岩12 h，白云岩72 h)，制备供质谱分析的 CO_2 气体.CO_2 气体的碳与氧同位素测试在中国科学院地质与地球物理研究所稳定同位素地球化学实验室MAT-253上完成.碳与氧同位素的测试值均相对于VPDB(vienna pee dee belemnite)国际标准；标准偏差分别不超过0.15‰和0.20‰.测试结果如表1.

表1 平南盆地寒武系碳酸盐岩的碳和氧稳定同位素组成

Table 1 Carbon and oxygen isotopes of the Cambrian carbonates from the Pyongnam basin

层位	岩石	样品号	$^{13}C_{carb}$ (‰，VPDB)	$^{18}O_{carb}$ (‰，VPDB)
古丰组	灰岩	16-Jc-33	−1	−13
	泥质灰岩	16-Jc-32	−0.9	−15.3
	泥质灰岩	16-Jc-31	−0.9	−15.6
	白云岩	16-Jc-30	0.4	−8.6
	白云岩	16-Jc-29	−0.6	−8.5
	白云岩	16-Jc-27	0.6	−11.4
	白云岩	15-S-17	1.8	−7.6
	白云岩	16-Jc-26	1.4	−11.7
	白云岩	15-S-15	0.4	−7.8
	灰岩	16-Jc-24	0.6	−10.3
	白云岩	15-S-14	0.9	−7.9
	粘土质灰岩	16-Jc-23	2.4	−9.9
	白云岩	16-Jc-22	0.2	−9.6
	白云岩	16-Jc-20	0.4	−10.3
	白云岩	16-Jc-19	0.4	−9.9
	白云岩	15-S-12	0.5	−7.8
	白云岩	15-S-10	0.7	−9.6
	白云岩	16-Jc-17	0.3	−10.7
戊辰组	泥灰岩	16-Jc-15	−0.2	−9.9
	粘土质灰岩	16-Jc-14	0.1	−13.8
	粘土质灰岩	16-Jc-13	0	−9.9
	灰岩	15-S-8	0.4	−9.7
	粘土质灰岩	16-Jc-12	0.3	−9.5
	灰岩	15-S-7	−1.3	−8.8
	粘土质灰岩	16-Jc-11	0.3	−9.2
林村组	灰岩	16-Ku-2	−0.8	−11.5
	灰岩	16-Jc-10	0.4	−14
	灰岩	16-Ku-1	−2.6	−8.1
	粘土质灰岩	16-Jc-9	−2.5	−12.1
	粘土质灰岩	16-Jc-7	−0.9	−10.3
	灰岩	16-Jc-6	−0.8	−12.6
	灰岩	16-Sh-2	0.1	−10.4
	灰岩	16-Sh-1	−0.3	−11.7
黑桥组	灰岩	14-J-24	−1.0	−11.7
	灰岩	14-J-20	0.2	−16.9
	灰岩	15-J-24	2.4	−10.5
	灰岩	15-J-23	1.2	−8.8

4 分析结果

前人已经发现在沉积物成岩过程中，大气水等流体会改变碳酸盐岩原来的碳同位素组成；并提出各种评价这些后期影响的方法(Veizer and Hoefs, 1976; Brand and Veizer, 1980; Derry *et al.*, 1992; Kaufman *et al.*, 1993; Kaufman and Knoll, 1995; Brasier *et al.*, 1996; Bartley *et al.*, 1998).本研究利用碳酸盐岩 $\delta^{13}C$ 和 $\delta^{18}O$ 之间的相互关系及 $\delta^{18}O$ 值的大小来判断测试值的有效性.从图4可以看出，

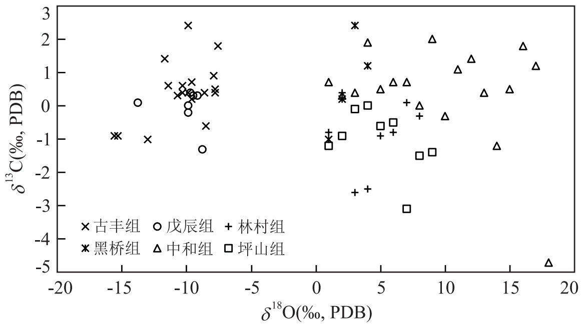

图 4　平南盆地寒武系碳酸盐岩 δ^{13}C-δ^{18}O 相关图

Fig.4　Correlation diagram of δ^{18}O and δ^{13}C of carbonates of the Cambrian carbonate rock in the Pyongnam basin

坪山组及中和组据金明哲等(2016)

大部分样品的 δ^{13}C 和 δ^{18}O 之间没有明显的相关关系，说明这些样品很可能记录了沉积的原始特征.

从表 1 和图 5 可以看出，黑桥组为 −1.0‰～2.4‰，平均值为 0.7‰；林村组 −2.6‰～0.4‰，平均值为 −0.9‰；戊辰组 −1.3‰～0.4‰，平均值为 0.1‰；古丰组为 −1.0‰～2.4‰，平均值为 0.4‰.其中，黑桥组底部出现很强的 δ^{13}C 正漂移.在林村组下部灰岩层和戊辰组底部出现明显的 δ^{13}C 负漂移，在古丰组中部出现正漂移.

5　讨论

5.1　生物地层学与区域地层对比

朝鲜平南盆地黄州群坪山组最底部砂岩碎屑锆石的年龄峰值为～1 850 Ma 和～2 500 Ma，另外也有 1 100～1 200 Ma 和 1 400～1 600 Ma 的次要年龄峰（杨正赫等，2016）；这些数据很好地说明其物源具有典型的华北克拉通属性.然而，这些数据不能限定坪山组及其上地层的确切时代.生物地层学对比可以提供限定.坪山组的 *Hsuaspis* 化石出现于寒武系最下部（Paterson，2005），因此可划定为中下寒武统.中和组上部钙质和泥质灰岩中的 *Kootenia* cf. *puntata*、*Girvanella manchurica* 和 Yabe et Ozaki 等类似化石出现在华南（四川）下寒武统的最后阶段（Zhang *et al*.，2017）.根据坪山组和中和组上部的三叶虫化石（Ameri and Zamani，2016），中和组的地层年龄为中－晚下寒武统.而 *Oryctocephalus longispinformis Kim*，*O. spiniger O. orientalis Saito O.* cf. *reynoldsi Saito*，*O. kobayashii Saito* 化石可能指示下中寒武统（Sundberg and McCollum，1997，2003）.黑桥组发现的 *Eosoptychoparia* sp.，*Oryctochephalus* sp.，*Peronopsis* sp.，*Proliostracus brevicaudatus Saito et Sakakura*，*Botsfordia granulate Redlich*，*Hyolithes* sp.等在早中寒武统被发现（Brasier，1984；Parcha，1999；Høyberget and Bruton，2008）.戊辰组鲕状灰岩中发现的 *Hyolithes* sp.和藻类化石，以及林村组黑色页岩中发现的海绵类化石，分别出现于中－晚中寒武统和中－中寒武统（Hong *et al*.，2012；Sanchez *et al*.，2017）.根据前人的研究，平南盆地的新元古界－古生界地层可以与邻区华北相关地层对比（Paek *et al*.，1996；Choi and Kim，1997；Park *et al*.，2001，2016；Kwon，2005；Kim，2010；Hu *et al*.，2012）.Peng *et al*.(2011)和朴贤旭等(2016)分别通过岩床的分布特征和碳同位素漂移特征提出平南盆地、辽东大连（旅大）盆地和徐淮盆地在新元古代可能属于同一裂谷系.金明哲等(2016)发现在平南盆地西南部燕滩群－黄州群获取的碳同位素数值显示与我国华南地区灯影组，以及世界其他地区相关地层（Oman 和 Moroco）相似的特征，推测燕滩群－黄州群大致对应埃迪卡拉系－下寒武统.根据彭善池(2009a，2009b，2014)对我国寒武纪三叶虫生物地层的对比研究，黄州群坪山组和中和组分别出现 *Hsuaspis coreanicus* 带和 *Redlichia chinensis* 带，表明它们分别不早于寒武系第三阶和第四阶.

5.2　寒武纪碳同位素及全球性事件

根据生物地层学对比，结合地层碳同位素变化特征（图 5），笔者认为，坪山组大致对应寒武系第二统第三阶，中和组和黑桥组大致对应第四阶，林村组大致对应苗岭统与第二统界线附近，戊辰组分别大致对应苗岭统的乌溜阶和第六－七阶，古丰组大致对应芙蓉统.无机碳同位素漂移的对应关系如下.

黑桥组下部出现的正漂移可以与 Zhu *et al*.(2006)命名的 MICE（mingxinsi carbon isotope excursion）事件对应（图 6），位于寒武纪第四阶，对应古杯动物群的大量繁盛（Zhu *et al*.，2006，2007）.生物的种属和多样性在此时增加.这次漂移出现在华南西部三叶虫化石 *Hupeidiscus fengdongensis* 附近（Zhang and Zhou，1985），说明在扬子地区 MICE 出现的位置为寒武纪的第三阶晚期到第四阶早期；我国三峡地区水井沱组含有三叶虫 *Hupeidicus orientalis*（湖北盘虫）（杨爱华等，2005），指示寒武世第三期晚期至第四期早期，Ishikawa *et al*.(2014)认为水井沱组上部地层碳同位素正漂移对应于寒武纪第四阶早期的 MICE 正漂移，但上述的正

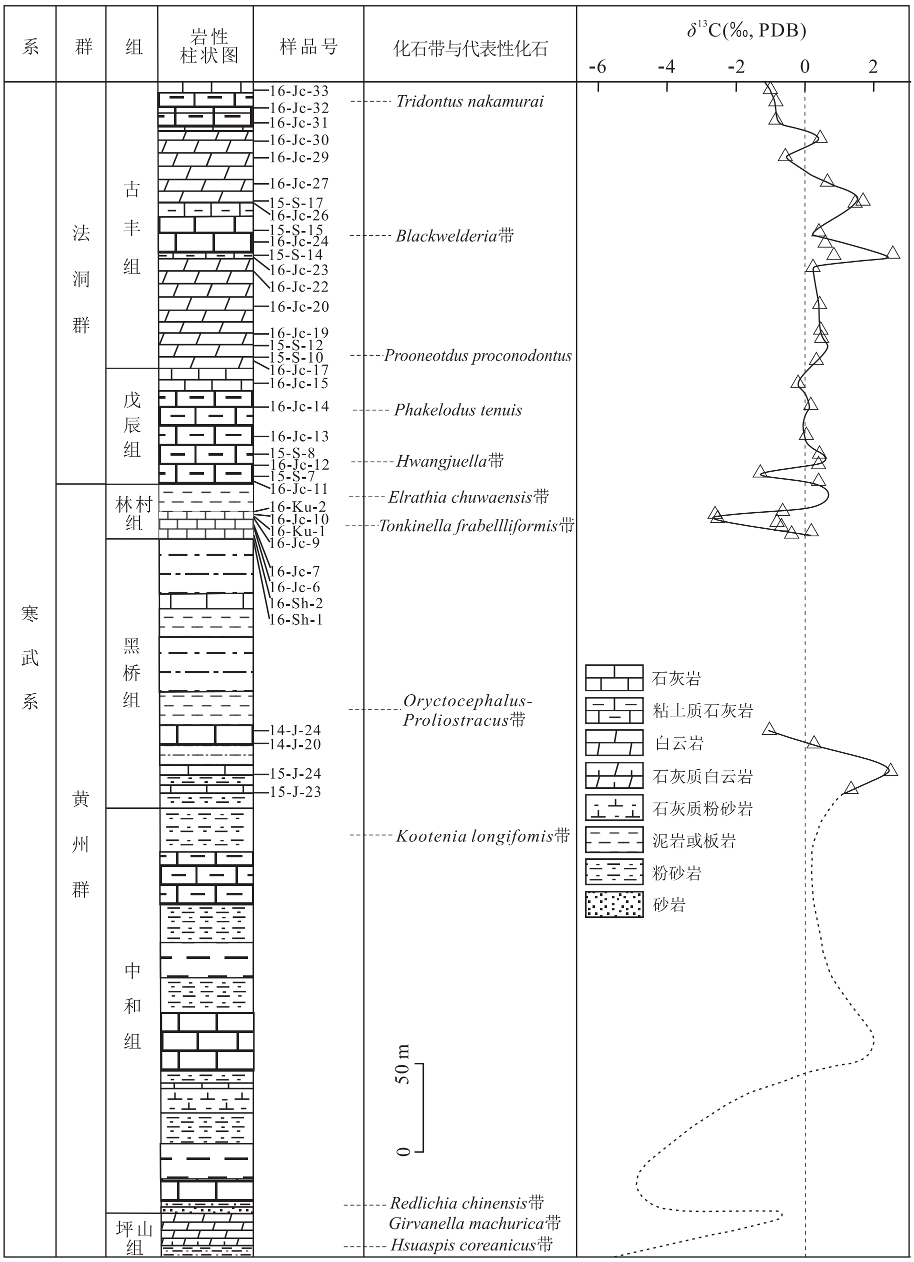

图 5 平南盆地寒武系地层柱状图及碳酸盐岩 $\delta^{13}C$ 值变化

Fig.5 Cambrian strata column and variation of the $\delta^{13}C$ values of carbonate samples in the Pyongnam basin

地层柱修改自 Paek *et al*.(1996),地层总厚度约 1 300 m.坪山组及中和组据金明哲等(2016)

漂移位置均早于 Zhu *et al*.(2006)命名的 MICE 事件的位置(Chang *et al*., 2017).与 MICE 事件可以对比的正漂移事件出现在中国华南地区(Ishikawa *et al*., 2014;王丹等,2016; Chang *et al*., 2017)、澳洲(Zhu *et al*., 2006)、西伯利亚(Brasier *et al*., 1994; Brasier and Sukhov, 1998)、加拿大(Dilliard *et al*., 2007)、摩洛哥(Maloof *et al*., 2010a, 2010b)等地.这一正漂移可能与初级生产力(Chang *et al*., 2017)和有机碳埋藏的增加(Ishikawa *et al*., 2014)有关.在生物繁盛时期,海洋初级生产力大幅提高,营养物质和氧气量增加,有机质埋藏增加,最终导致碳同位素的正漂移(Ishikawa *et al*., 2014;王丹等,2016).

林村组出现的负漂移可以对应于 Zhu *et al*.(2006)提及的位于寒武纪第二统-苗岭统(第四阶-乌溜阶)界线附近的 ROECE(redlichiid-olenellid extinction carbon isotope excursion)事件,即与 *Redlichiid* 和 *Olenellid* 绝灭层位相对应,$\delta^{13}C$ 峰值介于 4.0‰~7.9‰,在大西洋生物区,ROECE 事件对应于三叶虫 *Olenellid* 绝灭层位并伴随有

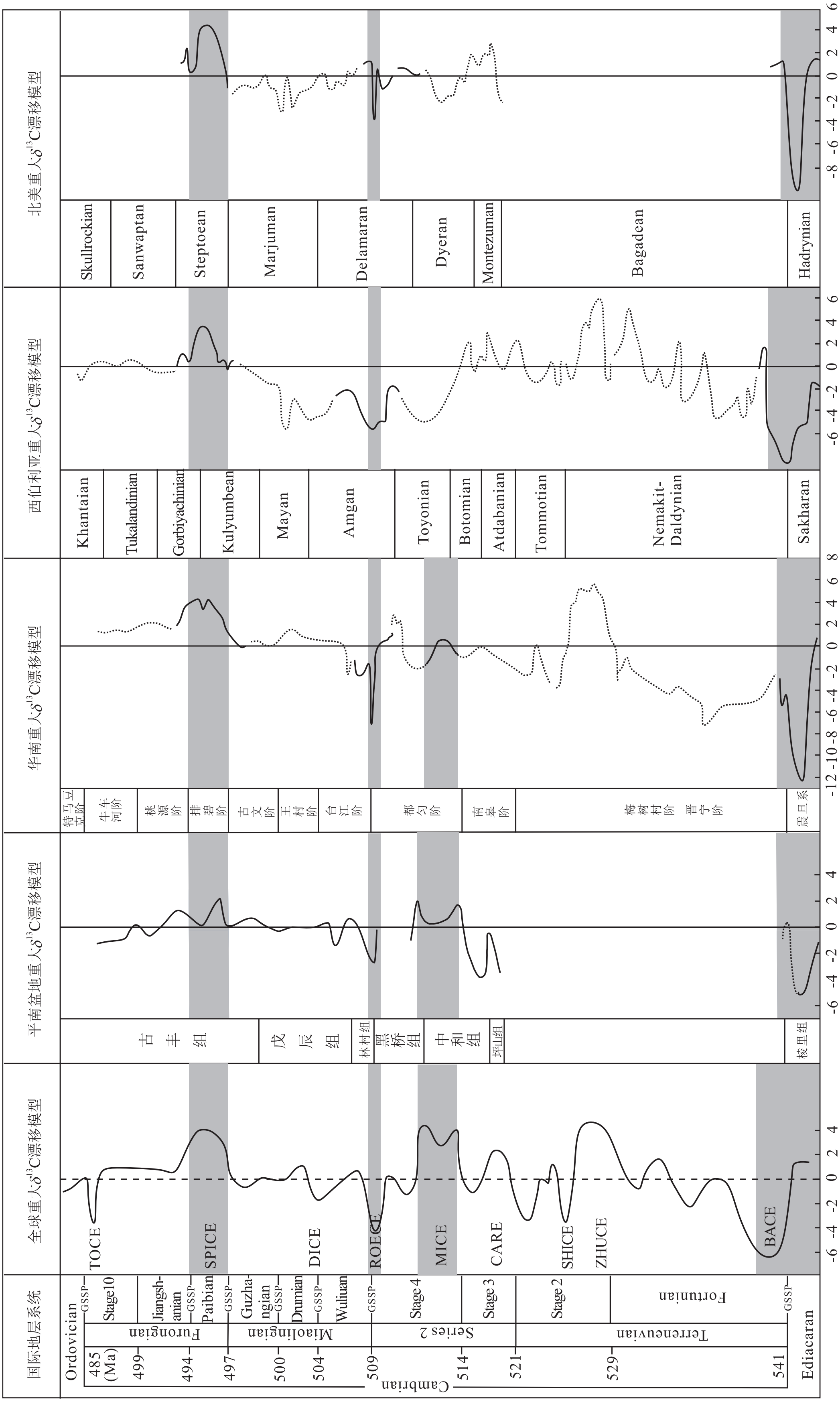

图 6　朝鲜平南盆地与华南、西伯利亚、北美等地寒武系碳酸盐岩碳同位素值变化对比

Fig. 6　Comparison of carbon isotope of the Cambrian carbonates in the Pyongnam basin with those equivalents in South China, Siberia and Northern America

改编自樊茹等(2011); 坪山组及中和组数据引自金明哲等(2016)

Paradoxides 的出现;在印度-太平洋生物区,对应于三叶虫 *Redlichiid* 绝灭层位(樊茹等,2011).这次事件在华南湘西北(Zhu *et al*., 2004)、安徽(Zhu *et al*., 2004)、贵州(杨瑞东等,2002; Guo *et al*., 2005, 2010),以及西冈瓦纳古陆(Wotte *et al*., 2007)、劳伦古陆(Dilliard *et al*.,2007)、西伯利亚古陆(Zhu *et al*., 2004)等地广泛出现.它出现在寒武系第二统-苗岭统界限附近(~509 Ma),可作为界定生物地层学全球标准的重要参照(樊茹等,2011). $\delta^{13}C$ 负漂移及其对应的三叶虫灭绝事件可能与一次海进事件及由此产生的古地理环境变化有关(Montañez *et al*., 2000).在西冈瓦纳(Wotte *et al*., 2007)、华南古陆(Zhu *et al*., 2004)、劳伦古陆(Dilliard *et al*., 2007)及西伯利亚(Brasier *et al*., 1994)等地广泛出现从碳酸盐岩过渡到页岩的进积层序(如华南凯里组),这为海平面上升提供了可靠证据(樊茹等,2011; Chang *et al*., 2017).海平面上升期,较轻的碳同位素在缺氧水体中形成上升流,从而造成台地相碳酸盐岩的 $\delta^{13}C$ 负漂移(Montañez *et al*., 2000).根据 Sr 同位素地层学数据,该时期大洋底部可能发生了一次由大规模火山活动导致的缺氧事件(Montañez *et al*., 2000),从而导致三叶虫动物群的灭绝和生物量骤减,有机碳埋藏量急剧减少,最终缺氧水体碳同位素组成发生负漂移.

法洞群古丰组中部存在与 Saltzman *et al*. (1998)命名的 SPICE(steptoean positive carbon isotope excursion)事件对应的正漂移.由 Brasier (1993)发现于美国西部大盆地 Steptoean 阶;其$\delta^{13}C$ 起始值约 0±1‰,峰值 3‰~5‰,漂移幅度平均约 4‰(樊茹等,2011).这一事件始于 *Glyptagnostus reticulates* 带的底部(Saltzman *et al*., 2000),结束于三叶虫 *Irvingella* 带底,时间跨度约 3.5 Ma (499.0~495.5 Ma),和一次全球性三叶虫灭绝时间相吻合(Walcott, 1913).在中国(Zhu *et al*., 2004;左景勋等,2008; Saltzman *et al*., 2000)、哈萨克斯坦(Saltzman *et al*., 1998)、西伯利亚(Kouchinsky *et al*., 2001, 2007, 2008)、北美(Brasier, 1993; Glumac and Walker, 1998; Montañez *et al*., 2000)、澳洲(Ripperdann *et al*., 1992; Lindsay *et al*., 2005)、南美(Buggisch *et al*., 2003)、欧洲(Ahlberg *et al*., 2006)等也有该事件出现.SPICE事件被普遍界定为一次海退事件,使得风化侵蚀速率增大,富^{12}C 的有机碳大量埋藏造成碳酸盐岩$\delta^{13}C$ 值发生正漂移(樊茹等,2011). Saltzman *et al*. (1998)提出海平面下降与有机碳埋藏的增加有关,大气 CO_2 浓度降低进而使得全球气温降低.鉴于在全球范围内未发现有同期富含有机质的暗色泥页岩沉积,Zhu *et al*. (2004)和 Glumac and Walker (1998)对上述观点提出质疑.除了与沉积物埋藏的增加有关,樊茹等(2011)还认为其可能与甲烷水化物的大量生成有关.Gill *et al*.(2011)在全球范围内发现 SPICE 事件时期碳-硫同位素均出现同步正漂移,这可能与有机碳和黄铁矿的大量埋藏有关.

6　结论

(1)黄州群和法洞群大部分样品的碳同位素很可能代表了原始沉积环境特征.黄州群自下而上的坪山组 $\delta^{13}C$ 值变化范围为 0~-3.1‰,中和组为 -4.7‰~2.0‰,黑桥组为-1.0‰~2.4‰,林村组为 -2.6‰~0.4‰;法洞群下部2个组中,下部戊辰组为-1.3‰~0.4‰,古丰组-1.0‰~2.4‰.

(2)基于生物地层学对比,结合地层碳同位素变化,笔者认为,坪山组大致对应寒武系第二统第三阶,中和组和黑桥组大致对应第四阶,林村组大致对应第二统与苗岭统界线附近,戊辰组对应苗岭统第六-七阶,古丰组大致对应芙蓉统.林村组和古丰组碳同位素负漂移可能具有全球对比意义.

(3)从黄州群和法洞群下部地层中可以识别出3个主要的全球性碳同位素事件,分别是中和组上部-黑桥组的 MICE 事件、林村组下部的 ROECE 事件以及古丰组中部的 SPICE 事件.其中,ROECE 为负漂移,MICE 和 SPICE 为正漂移.以上3个碳同位素漂移事件可能与早期生物的演化和气候环境的变化有关.

致谢:本文是中国科学院和朝鲜国家科学院合作团队集体成果;本文受国家自然科学基金项目(Nos.41772192,41322018)和中国科学院前沿重大基础项目(No.QYZDB-SSW-DQC04281712250)资助.感谢稳定同位素实验室冯连君高级工程师在实验过程中给予的帮助;感谢中国科学院地质与地球物理研究所周锡强博士的建议;感谢主编和三名匿名审稿人给出宝贵意见! 谨以此文纪念杨遵仪院士诞辰110周年.

References

Ahlberg, P., Axheimer, N., Eriksson, M. E., et al., 2006. High-Resolution Trilobite Biostratigraphy and Carbon

Isotope Stratigraphy of the Middle Cambrian-Lower Furongian of Baltica. In: Jago, J. B., ed., Material of the 11th International Conference of the Cambrian Stage Subdivision Working Group. *Geological Society of Australia Abstracts*, *South Australia*, 5.

Ameri, H., Zamani, F., 2016. Biostratigraphy of the Peri-Gondwana Cambrian Trilobite Fauna (Northern Kerman, Iran) and Correlation with Other Countries. *Historical Biology*, 28(3): 331−346. https://doi.org/10.1080/08912963.2014.927870

Bartley, J.K., Pope, M., Knoll, A.H., et al., 1998. A Vendian-Cambrian Boundary Succession from the Northwestern Margin of the Siberian Platform: Stratigraphy, Palaeontology, Chemostratigraphy and Correlation. *Geological Magazine*, 135(4): 473−494.

Berner, R. A., 2002. Examination of Hypotheses for the Permo-Triassic Boundary Extinction by Carbon Cycle Modeling. *Proceedings of the National Academy of Sciences*, 99(7): 4172−4177.

Brand, U., Veizer, J., 1980. Chemical Diagenesis of a Multicomponent Carbonate System-1: Trace Elements. *Journal of Sedimentary Research*, 50: 1219−1236.

Brasier, M. D., 1984. Microfossils and Small Shelly Fossils from the Lower Cambrian Hyolithes Limestone at Nuneaton, English Midlands. *Geological Magazine*, 121(3): 229−253.

Brasier, M. D, Sukhov, S. S., 1998. The Falling Amplitude of Carbon Isotopic Oscillations through the Lower to Middle Cambrian: Northern Siberia Data. *Canadian Journal of Earth Sciences*, 35(4): 353−373.

Brasier, M.D., 1993. Towards a Carbon Isotope Stratigraphy of the Cambrian System: Potential of the Great Basin Succession. *Geological Society*, *London*, *Special Publications*, 70(1): 341−350.

Brasier, M.D., Corfield, R.M., Derry, L.A., et al., 1994. Multiple $\delta^{13}C$ Excursions Spanning the Cambrian Exploration to the Botomian Crisis in Siberia. *Geology*, 22(5): 455−458.

Brasier, M.D., Shields, G., Kuleshov, V.N., et al., 1996. Integrated Chemo- and Biostratigraphic Calibration of Early Animal Evolution: Neoproterozoic-Early Cambrian of Southwest Mongolia. *Geological Magazine*, 133: 445−485.

Buggisch, W., Keller, M., Lehnert, O., 2003. Carbon Isotope Record of Late Cambrian to Early Ordovician Carbonates of the Argentine Precordillera. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 195(3−4): 357−373.

Chang, C., Hu, W. X., Wang, X. L., et al., 2017. Carbon Isotope Stratigraphy of the Lower to Middle Cambrian on the Eastern Yangtze Platform, South China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 479: 90−101. https://doi.org/10.1016/j.palaeo.2017.04.019

Choi, D. H., Kim, H. G., 1997. Stratigraphy and Lithofacies-Paleographic Properties of Lower Bed of Hwangju System, Hyonnae Area. *Geoprosecting*, 4: 11−12 (in Korean with English abstract).

Derry, L.A., Kaufman, A.J., Jacobsen, S.B., 1992. Sedimentary Cycling and Environmental Change in the Late Proterozoic: Evidence from Stable and Radiogenic Isotopes. *Geochimica et Cosmochimica Acta*, 56(3): 1317−1329.

Dilliard, K. A., Pope, M. C., Coniglio, M., et al., 2007. Stable Isotope Geochemistry of the Lower Cambrian Sekwi Formation, Northwest Territories, Canada: Implications for Ocean Chemistry and Secular Curve Generation. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 256(3): 174−194. https://doi.org/10.1016/j.palaeo.2007.02.031

Emrich, K., Ehhalt, D. H., Vogel, J. C., 1970. Carbon Isotope Fractionation during the Precipitation of Calcium Carbonate. *Earth and Planetary Science Letters*, 8(5): 363−371.

Fan, R., Deng, S. H., Zhang, X. L., 2011. Significant Carbon Isotope Excursions in the Cambrian and Their Implications for Global Correlations. *Science China Earth Sciences*, 41(12): 1829−1839 (in Chinese).

Gill, B.C., Lyons, T.W., Young, S.A., et al., 2011. Geochemical Evidence for Widespread Euxinia in the Later Cambrian Ocean. *Nature*, 469(7238): 80−83.

Glumac, B., Walker, K. R., 1998. A Late Cambrian Positive Carbon-Isotope Excursion in the Southern Appalachians: Relation to Biostratigraphy, Sequence Stratigraphy, Environments of Deposition, and Diagenesis. *Journal of Sedimentary Research*, 68(6): 1212−1222. https://doi.org/10.2110/jsr.68.1212

Guo, Q. J., Strauss, H., Liu, C. Q., et al., 2005. Carbon and Oxygen Isotopic Composition of Lower to Middle Cambrian Sediments at Taijiang, Guizhou Province, China. *Geological Magazine*, 142(6): 723−733.

Guo, Q. J., Strauss, H., Liu, C. Q., et al., 2010. A Negative Carbon Isotope Excursion Defines the Boundary from Cambrian Series 2 to Cambrian Series 3 on the Yangtze Platform, South China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 285(3): 143−151.

Hoffman, P. F., Kaufman, A. J., Halverson, G. P., 1998. Comings and Goings of Global Glaciations on a Neoproterozoic Tropical Platform in Namibia. *GSA Today*, 8(5): 1−9.

Hong, J., Cho, S.H., Choh, S.J., et al., 2012. Middle Cambrian Siliceous Sponge-Calcimicrobe Buildups (Daegi Formation, Korea): Metazoan Buildup Constituents in the Aftermath of the Early Cambrian Extinction Event. *Sedimentary Geology*, 253: 47—57.

Høyberget, M., Bruton, D. L., 2008. Middle Cambrian Trilobites of the Suborders Agnostina and Eodiscina from the Oslo Region, Norway. *Palaeontographica Abteilung a-Stuttgart-Band*, 286(1—3): 1—87.

Hu, B., Zhai, M. G., Li, T. S., et al., 2012. Mesoproterozoic Magmatic Events in the Eastern North China Craton and Their Tectonic Implications: Geochronological Evidence from Detrital Zircons in the Shandong Peninsula and North Korea. *Gondwana Research*, 22(3—4): 828—842.

Ishikawa, T., Ueno, Y., Shu, D., et al., 2014. The $\delta^{13}C$ Excursions Spanning the Cambrian Explosion to the Canglangpuian Mass Extinction in the Three Gorges Area, South China. *Gondwana Research*, 25(3): 1045—1056.

Jong, H. S., Hong, S., Won, C. G., 2001. Some Species of Cambrian Conodonts Found Newly in Dongmyongwangrung Area. *Bulletin of Kim Il Sung University*, 47(1): 138—141 (in Korean with English abstract).

Jong, H. S., Won, C., 2002. The Distribution of Cambrian Conodont Fossils in Ryokpo Area. *Bulletin of Kim Il Sung University*, 48(12): 98—102 (in Korean with English abstract).

Kaufman, A. J., Jacobsen, S. B., Knoll, A. H., 1993. The Vendian Record of Sr and C Isotopic Variations in Seawater: Implications for Tectonics and Paleoclimate. *Earth and Planetary Science Letters*, 120(3/4): 409—430. https://doi.org/10.1016/0012-821x(93)90254-7

Kaufman, A. J., Knoll, A. H., 1995. Neoproterozoic Variations in the C-Isotopic Composition of Seawater: Stratigraphic and Biogeochemical Implications. *Precambrian Research*, 73(1—4): 27—49. https://doi.org/10.1016/0301-9268(94)00070-8

Kim, C. J., 2010. Lithosfacies-Paleogeography during Sedimentation of Vendian Period. *Geological and Ore Deposit*, 5: 22—26.

Kim, D. S., 1978. Some Species of Trilobita Newly Found from the Lower Part of the Middle Cambrian Widely Distributed in the Northern Part of Korea. *Geology and Geography*, 2: 23—27 (in Korean with English abstract).

Kim, D. S., 1982. Boundary Problems of the Middle Cambrian in Korea. *Bulletin of Kim Il Sung University*, 3: 23—28 (in Korean with English abstract).

Kim, M. C., Yang, J. H., Peng, P., et al., 2016. Characteristics of Carbon Isotope of the Ediacaran and Lower Cambrian Strata in the Pyongnam Basin, DPR Korea. *Acta Petrologica Sinica*, 32(10): 3180—3186 (in Chinese with English abstract).

Kim, Y. G., 1988. Stratigraphic Significance of Brachiopods from the Cambrian of Pyongyang Area. *Geology and Geography*, 3: 29—31 (in Korean with English abstract).

Kirschvink, J. L., 1992. Late Proterozoic Low-Latitude Global Glaciation: The Snowball Earth. *The Proterozoic Biosphere*, 52: 51—52.

Kouchinsky, A., Bengtson, S., Gallet, Y., et al., 2008. The SPICE Carbon Isotope Excursion in Siberia: A Combined Study of the Upper Middle Cambrian-Lowermost Ordovician Kulyumbe River Section, Northwestern Siberian Platform. *Geological Magazine*, 145(5): 609—622.

Kouchinsky, A., Bengtson, S., Missarzhevsky, V. V., et al., 2001. Carbon Isotope Stratigraphy and the Problem of a Pre-Tommotian Stage in Siberia. *Geological Magazine*, 138(4): 387—396. https://doi.org/10.1017/s0016756801005684

Kouchinsky, A., Bengtson, S., Pavlov, V., et al., 2007. Carbon Isotope Stratigraphy of the Precambrian-Cambrian Sukharikha River Section, Northwestern Siberian Platform. *Geological Magazine*, 144(4): 609—618. https://doi.org/10.1017/s0016756807003354

Krull, E. S., Retallack, G. J., Campbell, H. J., et al., 2000. $\delta^{13}C_{org}$ Chemostratigraphy of the Permian-Triassic Boundary in the Maitai Group, New Zealand: Evidence for High-Latitudinal Methane Release. *New Zealand Journal of Geology & Geophysics*, 43(1): 21—32.

Kwon, J. M., 2005. Paleogepgraphic Properties of Lower Paleozoic. *Geoprospecting*, 4: 7—8 (in Korean with English abstract).

Kwon, J. R., Park M. H., Won C. K., et al., 2010. Stratigraphy of Korea (2). Kim Il Sung University Press, 13—81 (in Korean with English abstract).

Lindsay, J. F., Kruse, P. D., Green, O. R., et al., 2005. The Neoproterozoic-Cambrian Record in Australia: A Stable Isotope Study. *Precambrian Research*, 143(1—4): 113—133.

Maloof, A. C., Porter, S. M., Moore, J. L., et al., 2010a. The Earliest Cambrian Record of Animals and Ocean Geochemical Change. *Geological Society of America Bulletin*, 122(11—12): 1731—1774.

Maloof, A. C., Ramezani, J., Bowring, S. A., et al., 2010b. Constraints on Early Cambrian Carbon Cycling from the Duration of the Nemakit-Daldynian-Tommotian Boundary ^{13}C Shift, Morocco. *Geology*, 38(7): 623—626.

Montañez, I. P., Osleger, D. A., Banner J. L., et al., 2000. Evolution of the Sr and C Isotope Composition of Cambrian Oceans. *GSA Today*, 10: 1—7.

Paek, R. J., Kang, H. G., Jon, G. P., 1996. Geology of Korea.

DPR of Korea, Institute of Geology, State Academy of Sciences. Foreign Language Book Publishing House, Pyeongyang, 31－51.

Parcha, S.K., 1999. Cambrian Biostratigraphy in the Tethyan Sequences of the Spiti Valley, Himachal Himalaya, India. *Newsletters on Stratigraphy*, 37(3): 177－190.

Park, H.U., Zhai, M.G. Yang J.H., et al., 2016. Deposition Ages of the Sangwon Supergroup in the Pyongnam Basin (Korea) and the Early Tonian Negative Carbon Isotope Interval. *Acta Petrologica Sinica*, 32(7): 2181－2195 (in Chinese with English abstract).

Park, M.H., 2012. Geological Series of Korea (2). Industrial Publishing House, 309－363 (in Korean with English abstract).

Park, M.H., Ri, S.B., Kim, C.G., 2001. Lithos-Paleogeography in the Period of Deposition of Solhwasan System Muckchon Series in the Upper Proterozoic Era. *Bulletin of Kim Il Sung University*, 9: 160－163 (in Korean with English abstract).

Paterson, J.R., 2005. Revision of Discomesites and Estaingia (Trilobita) from the Lower Cambrian Cymbric Vale Formation, Western New South Wales: Taxonomic, Biostratigraphic and Biogeographic Implications. *Proceedings of the Linnean Society of New South Wales*, 126: 81－93.

Peng, S.C., 2009a. Review on the Studies of Cambrian Trilobite Faunas from Jiangnan Slope Belt, South China, with Notes on Cambrian Correlation between South and North China. *Acta Palaeontologica Sinica*, 48(3): 437－452 (in Chinese with English abstract).

Peng, S.C., 2009b. The Newly-Developed Cambrian Biostratigraphic Succession and Chronostratigraphic Scheme for South China. *Chinese Science Bulletin*, 54(18): 2691－2698 (in Chinese).

Peng S.C., 2014. Global Standard Stratotype-Section and Point (GSSP, "Golden Spike") and the GSSP Research in China. *Earth Science Frontiers*, 21(2): 8－26 (in Chinese with English abstract).

Peng, P., Zhai, M.G., Li, Q.L., et al., 2011. Neoproterozoic (～900 Ma) Sariwon Sills in North Korea: Geochronology, Geochemistry and Implications for the Evolution of the South-Eastern Margin of the North China Craton. *Gondwana Research*, 20(1): 243－254.

Ri, H., Ri, D.S., Won, C.G., 2009. On Some Species of Conodont Fossils Newly Found at Cambrian-Ordovician Boundary Strata in Resion Sopyong-ri Suan County. *Bulletin of Kim Il Sung University*, 55(3): 186－188 (in Korean with English abstract).

Ri, J.C., et al., 2010. Geological Series of Korea (5). Industrial Publishing House, 67-73 (in Korean with English abstract).

Ripperdan, R.L., Magaritz, M., Nicoll, R.S., et al., 1992. Simultaneous Changes in Carbon Isotopes, Sea Level, and Conodont Biozones within the Cambrian-Ordovician Boundary Interval at Black Mountain, Australia. *Geology*, 20(11): 1039－1042. https://doi.org/10.1130/0091-7613(1992)020<1039:scicis>2.3.co;2

Saltzman, M.R., Ripperdan, R.L., Brasier, M.D., et al., 2000. A Global Carbon Isotope Excursion (SPICE) during the Late Cambrian: Relation to Trilobite Extinctions, Organic-Matter Burial and Sea Level. *Palaeogeography Palaeoclimatology Palaeoecology*, 162(3/4): 211－223. https://doi.org/10.1016/s0031-0182(00)00128-0

Saltzman, M.R., Runnegar, B., Lohman, K.C., 1998. Carbon Isotope Stratigraphy of Upper Cambrian (Steptoean Stage) Sequences of the Eastern Great Basin: Record of a Global Oceanographic Event. *Geological Society of America Bulletin*, 110(3): 285－297. https://doi.org/10.1130/0016-7606(1998)110<0285:cisouc>2.3.co;2

Sanchez, B.E.B., Romero, F.J.C., Gonzalez, A.M., et al., 2017. The Echinoderm Gogia Granulosa (Echinodermata: Blastozoa) of Early-Mid Cambrian in Sonora, Mexico: Paleoecology and Paleogeography. *Revista de Biologia Tropical*, 65: 160－167.

Scholle, P.A., Arthur, M.A., 1980. Carbon Isotope Fluctuations in Cretaceous Pelagic Limestones: Potential Stratigraphic and Petroleum Exploration Tool. *AAPG Bulletin*, 64(1): 67－87.

Sundberg, F.A., McCollum, L.B., 1997. Oryctocephalids (Corynexochida: Trilobita) of the Lower-Middle Cambrian Boundary Interval from California and Nevada. *Journal of Paleontology*, 71(6): 1065－1090. https://doi.org/10.1017/s0022336000036040

Sundberg, F.A., McCollum, L.B., 2003. Early and Mid Cambrian Trilobites from the Outer-Shelf Deposits of Nevada and California, USA. *Palaeontology*, 46(5): 945－986. https://doi.org/10.1111/1475-4983.00328

Veizer, J., Hoefs, J., 1976. The Nature of $^{18}O/^{16}O$ and $^{13}C/^{12}C$ Secular Trends in Sedimentary Carbonate Rocks. *Geochimica et Cosmochimica Acta*, 40(11): 1387－1395.

Walcott, C.D., 1913. The Cambrian Faunas of China, Research in China 3. Carnegie Ins Washington Publication, Washington D.C., 54: 375.

Wang, D., Ling, H.F., Ulrich, S., et al., 2016. Organic Carbon Isotope Stratigraphy of the Early Cambrian Huitong Section in Hunan Province, Southeastern Yangtze, China. *Geological Journal of China Universities*, 22(2): 274－288 (in Chinese with English abstract).

Won, C.G., 2003. Cambrian Conodont Fossils Newly Found from Ryokpo Area. *Geological Prospecting*, 1: 11 (in Korean with English abstract).

Won, C.G., 2007. Observation on the Distribution of Cambrian Micropaleozoological Fossils of Kwail, Suan Areas. *Bulletin of Kim Il Sung University*, 53(10): 171－173 (in Korean with English abstract).

Won, C. G., Kim G. R., 2005. Micropaleozoological Fossils Newly Found from the Okrobong Beds of Junghwa Series in Hwangju Area. *Geological Prospecting*, 3: 10－11 (in Korean with English abstract).

Wotte, T., Álvaro, J.J., Shields, G.A., et al., 2007. C-, O- and Sr-Isotope Stratigraphy across the Lower-Middle Cambrian Transition of the Cantabrian Zone (Spain) and the Montagne Noire (France), West Gondwana. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 256(1－2): 47－70. https://doi.org/10.1016/j.palaeo.2007.09.002

Yang, A.H., Zhu, M.Y., Zhang, J.M., 2005. Stratigraphic Distribution and Palaeogeographic Control on the Early Cambrian Eodiscoids in Yangtze Platform. *Journal of Palaeogeography*, 7(2): 219－232 (in Chinese with English abstract).

Yang, Z.H., Peng, P., Jong, C.S., et al., 2016. Comparison on Ages of Detrital Zircons from the Paleoproterozoic to Lower Paleozoic Sedimentary Rocks in the Pyongnam Basin, Korea. *Acta Petrologica Sinica*, 32(10): 3155－3179 (in Chinese with English abstract).

Yang, R.D., Zhu, L.J., Wang, S.J., et al., 2002. Negative Carbon Isotope Excursion at the Middle-Lower Cambrian Boundary of Taijiang, Guizhou Province, China: Implication for Biological and Stratigraphical Significance. *Science in China (Series D)*, 32(6): 500－506 (in Chinese).

Zhang, M.Q., Hong, J., Choh, S.J., et al., 2017. Thrombolite Reefs with Archaeocyaths from the Xiannüdong Formation (Cambrian Series 2), Sichuan, China: Implications for Early Paleozoic Bioconstruction. *Geosciences Journal*, 21(5): 655－666.

Zhang, Q., Zhou, Z., 1985. Early Cambrian Trilobite Fauna of Kunshan, Jiangsu. *Acta Palaeontologica Sinica*, 24: 259－266.

Zhu, M.Y., Babcock, L.E, Peng, S.C., 2006. Advances in Cambrian Stratigraphy and Paleontology: Integrating Correlation Techniques, Paleobiology, Taphonomy and Paleoenvironmental Reconstruction. *Palaeoworld*, 15(3/4): 217－222.

Zhu, M. Y., Strauss, H., Shields, G. A., 2007. From Snowball Earth to the Cambrian Bioradiation: Calibration of Ediacaran-Cambrian Earth History in South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 254(1/2): 1－6.

Zhu, M. Y., Zhang, J. M., Li, G. X., et al., 2004. Evolution of Clsotopes in the Cambrian of China: Implications for Cambrian Subdivision and Trilobite Mass Extinctions. *Geobios*, 37(2): 287－301.

Zuo, J.X., Peng, S.C., Zhu, X.J., 2008. Carbon Isotope Composition of Cambrian Carbonate Rocks in Yangtze Platform, South China and Its Geological Implications. *Geochimica*, 37(2): 118－128 (in Chinese with English abstract).

附中文参考文献

樊茹，邓胜徽，张学磊，等，2011.寒武系碳同位素漂移事件的全球对比性分析.中国科学：地球科学，41(12)：1829－1839.

金明哲，杨正赫，彭澎，等，2016.朝鲜平南盆地埃迪卡拉系－下寒武统地层碳同位素特征.岩石学报，32(10)：3180－3186.

彭善池，2009a.华南斜坡相寒武纪三叶虫动物群研究回顾并论我国南、北方寒武系的对比.古生物学报，48(3)：437－452.

彭善池，2009b.华南新的寒武纪生物地层序列和年代地层系统.科学通报，54(18)：2691－2698.

彭善池，2014.全球标准层型剖面和点位（"金钉子"）和中国的"金钉子"研究.地学前缘，21(2)：8－26.

朴贤旭，翟明国，杨正赫，等，2016.朝鲜平南盆地祥原超群的沉积时代与拉伸纪早期碳同位素负漂移.岩石学报，32(7)：2181－2195.

王丹，凌洪飞，ULRICH Struck，等，2016.湖南会同寒武纪早期有机碳同位素地层学研究.高校地质学报，22(2)：274－288.

杨爱华，朱茂炎，张俊明，2005.扬子地台早寒武世古盘虫类的地层分布及其古地理控制.古地理学报，7(2)：219－232.

杨瑞东，朱立军，王世杰，等，2002.贵州台江中、下寒武统界线附近碳同位素负异常的生物和地层意义.中国科学(D辑)：地球科学，32(6)：500－506.

杨正赫，彭澎，郑哲寿，等，2016.朝鲜平南盆地古元古界－下古生界沉积岩碎屑锆石年龄谱对比及意义.岩石学报，32(10)：3155－3179.

左景勋，彭善池，朱学剑，2008.扬子地台寒武系碳酸盐岩的碳同位素组成及地质意义.地球化学，37(2)：118－128.