扬子地区震旦纪—寒武纪转折期大陆风化研究进展与展望

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内容提要: 通过调研扬子地区震旦纪(埃迪卡拉纪)—寒武纪(E—C)转折期大陆风化、海洋环境和有机质富集特征研究。结果显示,扬子地区E—C转折期遭受了较强烈的化学风化作用,且在这一时期区内兼具浅水碳酸盐台地和深水盆地环境。在台地相区,下寒武统牛蹄塘组黑色岩系不整合接触于震旦系灯影组白云岩之上,该不整合与E—C转折期全球"大不整合"具有紧密的关系,盆地区发育的完整的沉积地层记录了台地区被风化地层的痕迹。现有大陆风化的地球化学证据集中于$n(^{87}Sr)/n(^{86}Sr)$、$\delta^{13}C$、*CIA*和$\varepsilon_{Nd}(t)$等,同时这些地球化学数据也局限在少数的剖面和层段,因此迫切需要更多的地球化学参数来反映该风化作用的影响范围和演化特征。准确认识扬子地区E—C转折期大陆风化作用与海洋环境演变间的耦合关系,是揭示古生物演化、有机质富集机制的重要环节。

关键词: 扬子地区;埃迪卡拉纪—寒武纪转折期;震旦纪—寒武纪转折期;大陆风化;海洋环境;有机质

震旦纪(埃迪卡拉纪)—寒武纪(E—C)转折期同时发生了超大陆的裂解(Rodinia)与聚合(Gondwana)(Li Da et al., 2013; Yao Weihua et al., 2014)、海洋化学与生物化学的动荡变化(Hoffman et al., 1998; Fike et al., 2006; McFadden et al., 2008; Och et al., 2013; Sahoo et al., 2012; Li Da et al., 2013)、生命的幕式更替(张文堂,1997; Zhang Xingliang et al., 2014; 朱茂炎等,2019)等重大地质事件。其中,最引人注目的是新元古代末期埃迪卡拉纪动物群的消失,以及随后从早寒武纪开始的骨骼化动物爆发辐射(即"寒武纪生命大爆发")。普遍认为,E—C转折期大气氧浓度的持续增加(图1)以及海水氧化还原条件的动态变化在早期生命演化过程中起着显著的作用(Li Chao et al., 2010; Och et al., 2013; Wen Hanjie et al., 2015; Li Weiping et al., 2017; 朱茂炎等,2010,2019)。然而,目前对这一时期大气氧浓度和海洋氧化还原条件变化的驱动力仍然没有定论。

大陆风化是全球元素循环的关键环节,将大陆地壳的元素释放到空气、植物和河流中,然后流向海洋(Brantley et al., 2011; Teng Fangzhen et al., 2020)。大陆风化作用能够将地表巨量的离子和营养盐输送至海洋,引发海水的富营养化和海洋酸化,进而导致海水缺氧、透光带降低等危及当时海洋中生命生存的环境系统,这一效应积累到海洋生命所能承受的阈值后,最终引发海洋生态系统的崩溃并造成生物的大量灭绝(Lenton and Watson, 2004; Riding and Liang, 2005; Yan Detian et al., 2010; Poulton et al., 2015; Sun He et al., 2018; Jin Chengsheng et al., 2020; Wei Guangyi et al., 2020)。同时,大陆风化作用带来的SO_4^{2-}能够氧化有机质,产生H_2S和低$\delta^{13}C$值CO_2,造成海水逐渐硫化和海水中溶解无机碳$\delta^{13}C$值降低(Zhai Lina et al., 2018; Li Weiping et al., 2019)。碳酸盐的风化向大气输入低$\delta^{13}C$值CO_2,进而通过与海水交换,也会造成海水中溶解无机碳$\delta^{13}C$值降低(Lyons et al.,

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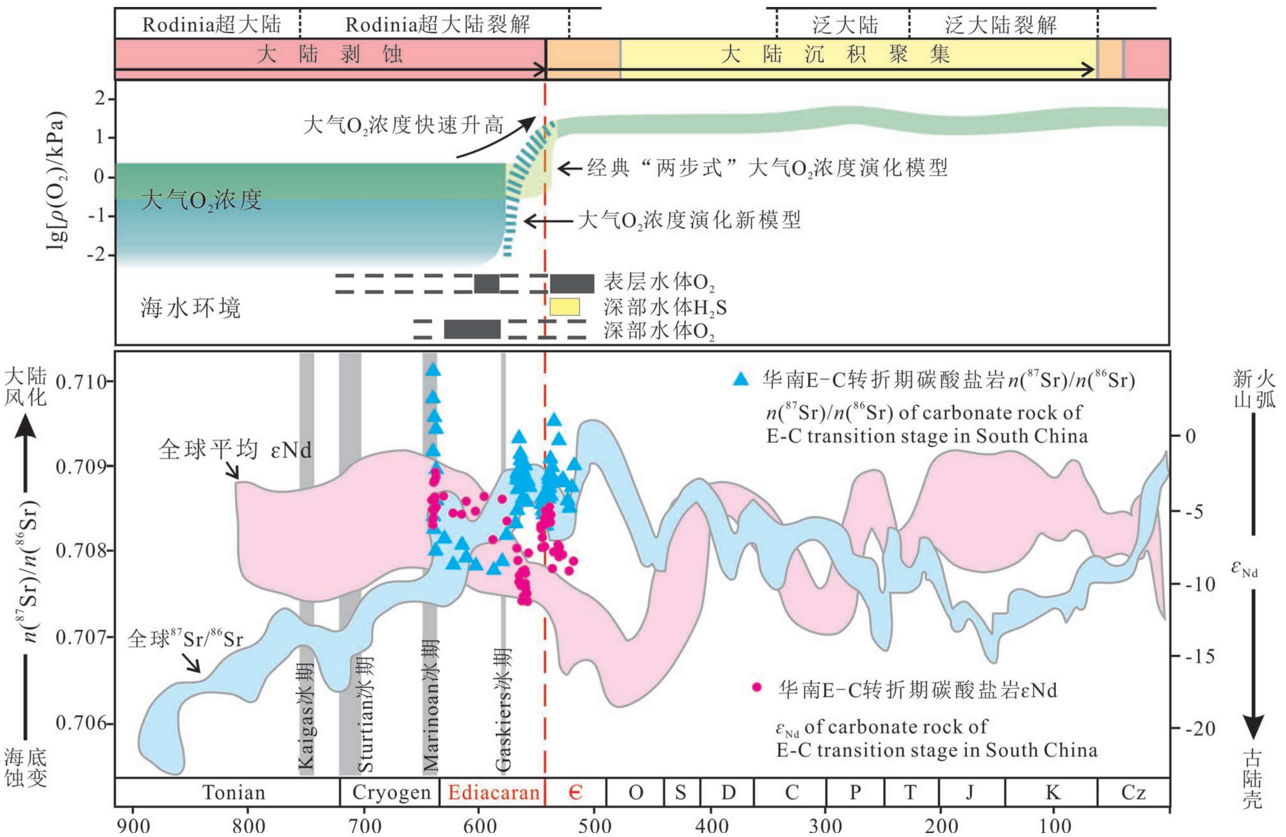


图 1 新元古代以来构造、地球化学特征及大气氧气浓度(大气氧含量参考 Kump et al., 2007; Lyons et al., 2014;海水环境参考 Canfield et al., 2008;全球$n(^{87}Sr)/n(^{86}Sr)$、ε_{Nd} 数据及构造活动等参考 Hoffman and Li, 2009; Peter and Gaines, 2012;华南 E—C 转折期$n(^{87}Sr)/n(^{86}Sr)$、ε_{Nd} 参考 Wei Guangyi et sl., 2019; Li Meng et al., 2020)

Fig. 1 Characteristics of tectonic movements, geochemistry, and atmospheric oxygen concentration (oxygen concentration is from Kump et al., 2007, Lyons et al., 2014; Marine environment is from Camfield et al., 2008; Global $n(^{87}Sr)/n(^{86}Sr)$, ε_{Nd}, and tectonic movements are from Hoffman and Li, 2009, Peter and Gaines, 2012; $n(^{87}Sr)/n(^{86}Sr)$ and ε_{Nd} in South China are Wei Guangyi et al., 2019, Li Meng et al., 2020)

2014; Li Weiping et al., 2017, 2019; Wei Guangyi et al., 2018)。上述研究表明,大陆风化在地质时间尺度上驱动大气圈、水圈、生物圈和大陆地壳的化学演化,是海洋环境演化的重要驱动力之一,进而影响着生命演化和有机质富集。

前寒武纪末期,地球气候曾发生剧烈的波动,并出现四次影响深远的冰期气候(图 1)(Hoffman and Li, 2009; Zhou Chuanming et al., 2019; Li Minglong et al., 2019;李明龙等,2021)。在冰期气候之后,冰川的迅速消融使地球进入温室气候,导致前寒武纪末期化学风化强度迅速增强(Hoffman et al., 1998; Peter and Gaines, 2012)。随后在早寒武世期间广泛的海侵和基底改造,使寒武系不整合沉积于前寒武纪风化地层之上,导致 E—C 转折期“大不整合(Great unconformity)”的形成(Peter and Gaines, 2012; Shahkarami et al., 2020)。“大不整合”具有全球规模,在 E—C 转折期各主要大陆均有分布(图 2),并且该不整合面具有穿时特征。例如,在西伯利亚、外蒙古、挪威等地发育在埃迪卡拉系上统内部,以碎屑角砾岩层不整合覆盖于碳酸盐岩层之上为特征(Nielsen and Schovsbo, 2011; Smith et al., 2015; Markov et al., 2019);在加拿大麦肯锡、美国加利福尼亚等地区表现为黑色细粒沉积岩系与下伏碳酸盐岩或角砾岩之间的不整合接触(Peter and Gaines, 2012; Smith et al., 2016);在澳大利亚弗林德斯,该不整合面为埃迪卡拉系与寒武系的界线,寒武系含砾砂岩不整合覆盖于埃迪卡拉系碳酸盐岩之上(Mapstone and Mcllry, 2006);我国扬子地区,该不整合面同样是埃迪卡拉系与寒武系的界线,但不整合面之上为下寒武统黑色细粒岩系,有机质丰富

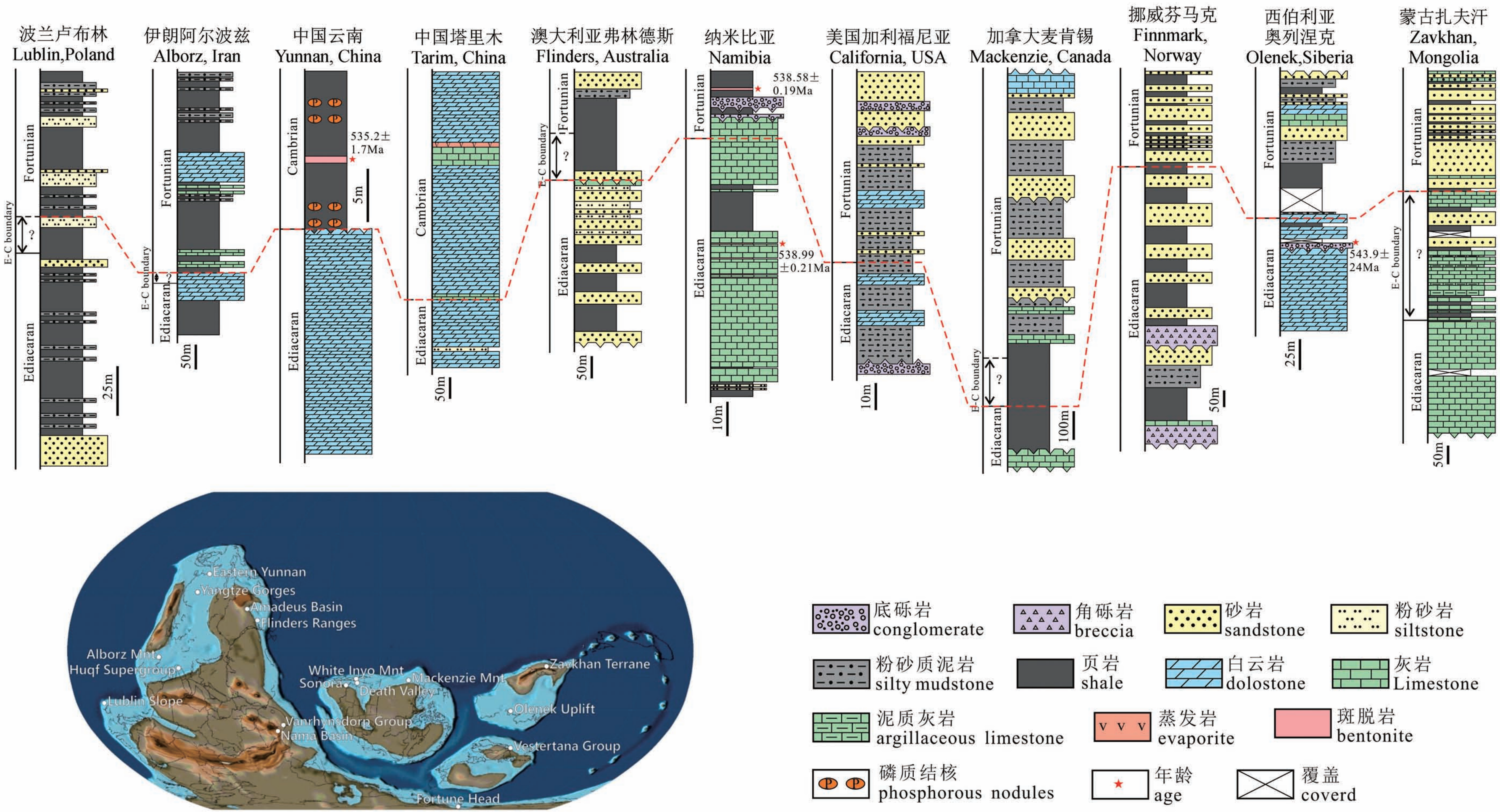


图2 全球不同地区E—C转折期地层和岩性特征

Fig. 2 Strata and lithology of E—C transition stage around the world

古板块分布参考/The distribution of palaeo-plate is from: Scotese, 2016. 地层和岩性参考/Strata and lithology are from: Mapstone and Mcllry, 2006; Zhu Maoyan, 2010;Nielsen and Schovsbo, 2011; Smith et al., 2015, 2016; Linnemann et al., 2019; Markov et al., 2019; Zhu Maoyan et al., 2019; Shahkarami et al., 2020; Zhang Yinggang et al., 2020

(Zhu Maoyan et al., 2010, 2019; Li Chao et al., 2020);在纳米比亚,该不整合面位于埃迪卡拉系与寒武系的界线以上,为寒武系底砾岩与下伏埃迪卡拉系碳酸盐岩的不整合接触(Linnemann et al., 2019)。E—C 转折期"大不整合"的出现与这一时期海水环境和大气氧浓度变化存在较好的对应关系(图 1),暗示"大不整合"形成过程中产生的大量风化产物输入海洋,驱动早寒武世海洋环境变化,触发"寒武纪生命大爆发"(Peter and Gaines, 2012)。然而,"大不整合"的分布特征(图 2)反映 E—C 转折期不同地区大陆风化特征存在明显差异。

本文以扬子地区 E—C 转折期为例,学习和总结了关于这一时期古大陆风化、古海洋环境演化以及有机质富集特征方面的研究进展,讨论了大陆风化与古海洋环境的协同演化关系及相关问题。

2 大陆风化作用强度研究方法

2.1 化学蚀变指数

上地壳遭受化学风化的过程中,K^+、Na^+、Ca^{2+}等离子活性强,容易随地表流体大量流失,然而,Al^{3+}、Ti^{4+}等离子较稳定,容易保存在风化残留物中,导致风化残留物中主成分 Al_2O_3 所占的比重随风化作用强度而不断变化。据此,Nesbitt 和 Young(1982, 1989)将"化学蚀变指数"(chemical index of alteration, *CIA*)作为评价物源区风化强度和气候条件的指标,即:

$$CIA=\frac{n(Al_2O_3)}{n(Al_2O_3)+n(CaO^*)+n(K_2O)+n(Na_2O)}$$

其中 $n(CaO^*)$ 为硅酸盐矿物中的 CaO。高的 *CIA* 值反映较强烈的化学风化作用,对应温暖潮湿的气候条件,K^+、Na^+、Ca^{2+} 等易迁移阳离子大量去除,Al^{3+}、Ti^{4+}等难迁移阳离子逐渐在风化残余物中富集。低 *CIA* 值反映化学风化作用较弱甚至不存在,对应寒冷干燥的气候条件。未经风化的沉积岩 *CIA* 标准值为 48(Rudnick and Gao Shan, 2014),遭受风化后的沉积物 *CIA* 值高于该标准值,并且随风化强烈程度增加而不断升高(Nesbitt and Young, 1982, 1989)。

基于上述理论基础,*CIA* 在化学风化强度研究方面得到了广泛应用,例如,我国南方新元古代古城冰期和南沱冰期细碎屑岩 *CIA* 值较低,分布在 56.5~64.6,均值约 59.8,反映物源区经历了轻微的化学风化作用(冯连君等,2003;熊晨,2019;李明龙等,2021),与冰期寒冷干燥的气候相对应;晚奥陶世五峰组—早志留世龙马溪组碎屑岩 *CIA* 值为 75~90,反映物源区经历了较强烈的化学风化(Yan Detian et al., 2010)。然而,*CIA* 是基于化学组成相对均一的岩石建立的(Ohta et al., 2007),受原岩成分影响大,钾交代作用、变质作用、古老沉积岩的再循环沉积等会改变原岩成分,进而制约 *CIA* 判断风化强度的准确性。因此在应用 *CIA* 指标时不仅对样品的选取有严格的要求,还需结合校正公式去除钾交代的影响(Panahi et al., 2000; Zhai Lina et al., 2018),以及结合 *ICV*(成分变异指数,index of compositional variability)和 Th/Sc—Zr/Sc、A—CN—K 等图解评价沉积分选及再循环作用(冯连君等, 2003; Yan Detian et al., 2010;吴蓓娟等,2016)。结合这些参数能够在一定程度上强化 *CIA* 判断化学风化的准确性,但在评价化学组成极不均一的黑色页岩时仍然存在较大分歧,以我国南方主要页岩气储层—龙马溪组黑色页岩—为例,经过钾交代校正后 *CIA* 值可达 90,反映极强烈的化学风化作用(Yan Detian et al., 2010),但近期的研究显示该黑色页岩受成岩及交代作用影响较小,*CIA* 平均值为 66,风化作用强度较小(张茜等,2020),这可能是受样品较高的碳酸盐矿物含量的影响,同时黑色页岩的强非均质性也是可能的影响因素。针对湘中下寒武统黑色页岩,吴蓓娟等(2016)成功构建了 *WB* 指数评价其风化程度,但该指数是基于现今黑色页岩风化特征的评价,对其评价地质历史中黑色页岩风化强度的适用性还需进一步证实。可见,采用 *CIA* 单一指标评价风化强度很难得到可靠的结果,通常将 *CIA* 与同位素地球化学指标相结合判断大陆风化作用。

2.2 同位素地球化学指标

2.2.1 Sr 同位素

海水中的 Sr 主要有大陆风化输入和海底热液两种来源,其中,大陆风化作用提供的 Sr 相对富^{87}Sr[具放射性,$n(^{87}Sr)/n(^{86}Sr)=0.7119$](Palmer and Edmond, 1989),海底热液活动提供的 Sr 相对富^{86}Sr($n(^{87}Sr)/n(^{86}Sr)=0.703$)(Holland, 1984)。溶解 Sr 在海水中停留时间(2~3 Ma)远长于海水混合时间(1~1.5 ka),所以海水的 Sr 同位素比值 $n(^{87}Sr)/n(^{86}Sr)$ 在任何时间均被认为是均一的(McArthur et al., 2012),那么原生海底沉积物和自生矿物中 Sr 同位素比值,反映的是大陆风化作用来源 Sr 和热液活动来源 Sr 的动态平衡。因此,海水 $n(^{87}Sr)/n(^{86}Sr)$ 值能够反映风化作用强度(或造山作用)与洋壳增生速度(或火山—热液活动强度),

并对构造演化和气候变化(或 $P(CO_2)$)进行约束(Jenkyns et al., 2002; Wang Wei et al., 2007;王文倩等,2014)。

如图 1,新元古代至寒武纪,古海洋 $n(^{87}Sr)/n(^{86}Sr)$ 持续升高,这一时期正好对应 Rodinia 大陆的裂解、剥蚀,形成“大不整合”(Peters and Gaines, 2012),显示了 Sr 同位素变化对大陆风化作用的良好响应。在华南、北美、蒙古、西伯利亚、阿拉伯半岛和南非等地均存在 E—C 转折期高 $n(^{87}Sr)/n(^{86}Sr)$ 值(0.707~0.711)(Sawaki et al., 2008; Li Da et al., 2013; Wei Guangyi et al., 2019),表明在 E—C 转折期,强烈的化学风化作用遍及全球大部分地区,形成的“大不整合”具有全球规模(Shahkarami et al., 2020)(图 2)。尽管海水 Sr 同位素组成在示踪大陆风化方面取得了较多成功的运用,但 Sr 同位素易受原岩(主要是碳酸盐岩)性质的影响,因此通过海洋沉积的 Sr 同位素示踪大陆风化过程存在多解性。

2.2.2 Os 同位素

海水中 Os 元素主要有三种来源:① 大陆地壳中 Os 经河流带入;② 洋中脊热液蚀变来源;③ 宇宙尘埃来源。大陆地壳 Os 同位素富集放射性 ^{187}Os,$n(^{187}Os)/n(^{188}Os)$ 值较高,现今陆源输入 $n(^{187}Os)/n(^{188}Os)$ 平均值为 1.54(Levasseur et al., 1999; Cohen et al., 2004)(图 3)。洋中脊热液蚀变来源和宇宙尘埃来源的 Os 为非放射性成因,并且两种来源 Os 具有相近的 $n(^{187}Os)/n(^{188}Os)$ 值,约为 0.126,远低于大陆地壳风化来源 Os 的 $n(^{187}Os)/n(^{188}Os)$ 值。海水中 Os 元素的组成特征主要是这三种来源的综合结果,其中约 80%来自陆源输入,仅 20%来源于海底热液蚀变和宇宙尘埃(Sharma and Wasserburg, 1997),因此可以通过海水

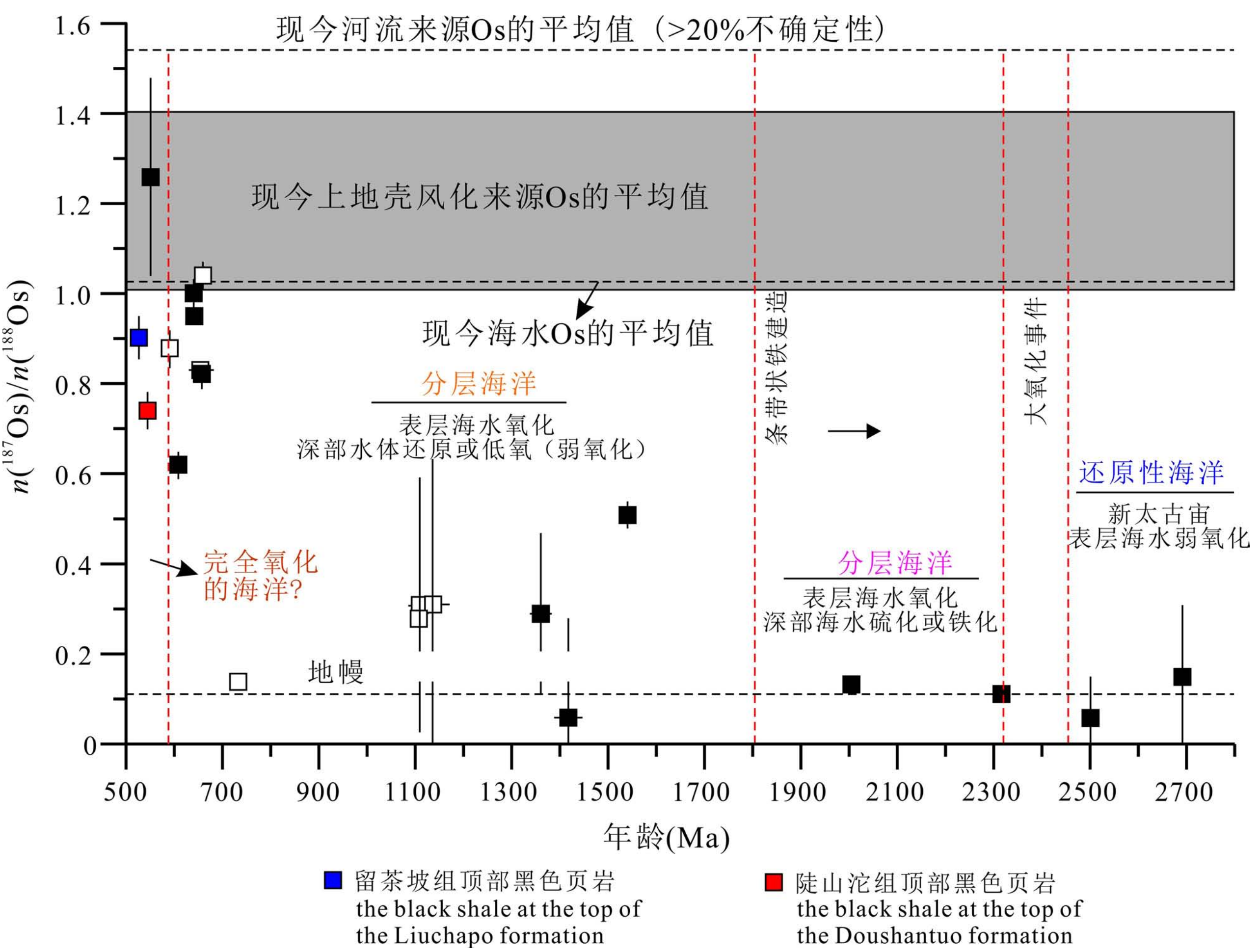


图 3 前寒武纪海水初始 $n(^{187}Os)/n(^{188}Os)$ 值(数据引自 Kendall et al., 2009; Rooney et al., 2010, 2011; Zhu Bi et al., 2013)

Fig. 3 Initial $n(^{187}Os)/n(^{188}Os)$ of marine water of Precambrian (data are from Kendall et al., 2009; Rooney et al., 2010, 2011; Zhu Bi et al., 2013)

Os 同位素的变化来约束大陆风化强度和海底热液喷发等过程(Cohen, 2004; Zhu Bi et al., 2013; Tripathy et al., 2018)。

强烈的化学风化作用对应高的 $n(^{187}Os)/n(^{188}Os)$ 值，例如，近 50 Ma 以来，海水 $n(^{187}Os)/n(^{188}Os)$ 值逐渐升高，与海水的 Sr 同位素组成升高的趋势一致，反映这一时期喜马拉雅抬升运动造成的大陆风化强度逐渐增强(Pegram et al., 1992)。英格兰 Yorkshire 早侏罗世经历了温暖湿润的古气候和强烈的化学风化，对应的含砾石黑色页岩段 $n(^{187}Os)/n(^{188}Os)$ 值为 0.8～1.0，$n(^{87}Sr)/n(^{86}Sr)$ 值由 0.70706 迅速升至 0.70720(Cohen et al., 2004)。新元古代晚期，苏格兰、爱尔兰、毛里塔尼亚以及中国等均显示海水初始 $n(^{187}Os)/n(^{188}Os)$ 值迅速升高(图 3)，反映这一时期存在强烈的化学风化作用(Zhu Bi et al., 2013)，与“大不整合”的时间相当(Peters and Gaines, et al., 2012; Li Meng et al., 2020; Shahkarami et al., 2020)，说明海洋 $n(^{187}Os)/n(^{188}Os)$ 值的变化对“大不整合”有较好的响应，能够反映地质时期的化学风化强度。然而，黑色岩系(主要是黑色页岩)富集有机质和硫化物会大量吸附海水中 Os，导致黑色岩系中 Os 异常富集，因此 Os 同位素示踪黑色岩系的大陆风化过程存在多解性。

2.2.3 Li 同位素

Li 同位素在示踪大陆硅酸岩风化方面具有以下优势：① 化合价单一，不受氧化还原状态影响；② 大陆硅酸岩地壳具有相对较高的 Li 含量(李东永等，2019)，且在风化过程中可以产生极大分馏(Rudnick et al., 2004; Tomascak., 2004)；③ 不受生物过程影响(Rudnick et al., 2004; Penniston-Dorland et al., 2017)。因此，所有地质过程中 Li 同位素的分馏发生在大陆风化作用过程中(Rudnick et al., 2004; Henchiri et al., 2014)。目前已经基本获得自然储库中 Li 的丰度和 δ^7Li 值(图 4)，为 Li 同位素示踪大陆风化研究奠定了基础。由于 Li 是水溶性元素，受淋溶作用易迁移至溶液中，经搬运注入海洋。Li 的同位素分馏主要发生在搬运过程中，在淋溶过程中仅仅发生微弱的同位素分馏(Wimpenny et al., 2010a, 2010b; Verney-Carron et al., 2011)。搬运过程中，^6Li 优先在次生黏土矿物中富集，造成黏土矿物中 Li 含量高(平均约为 80 μg/g)，δ^7Li 值相对较低(1.6‰～5.0‰)；大部分 ^7Li 跟随流体注入海洋，并在俯冲过程中被带到下地壳或者地幔，导致上地壳富集 ^6Li(Marschall et al., 2007; Steinhoefel et al., 2021)。

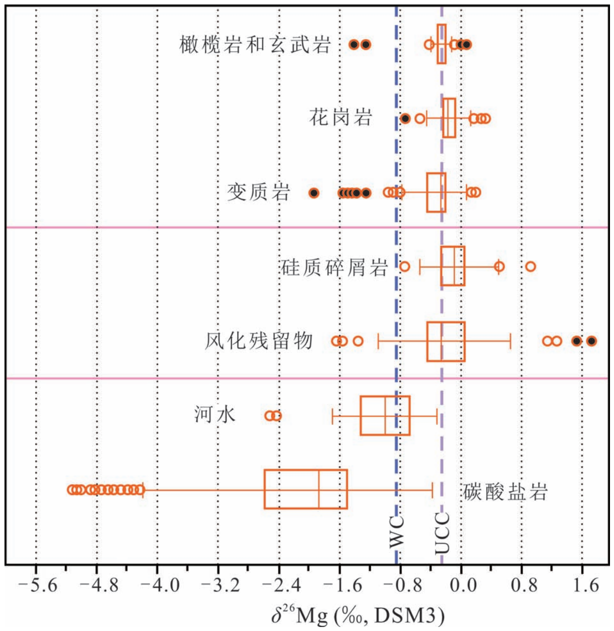


图 4 自然储库中 Li 同位素(苟龙飞等，2017)和 Mg 同位素(Huang Jinxiang et al., 2016)的分布

Fig. 4 Lithium(Gou Longfei et al., 2017&) and magnesium (Huang Jinxiang et al., 2016) isotopic composition in natural reservoir

Li 同位素已被成功运用到示踪大陆风化过程的多项研究中：太古宙 3.0～2.9 Ga 期间，快速的大陆风化作用导致海水 δ^7Li 值降低，远低于现代海水(付露露等，2020)；在 445 Ma 的 Hirnantian 冰期，大陆风化强度降低，海水 δ^7Li 值明显升高(von Strandmann et al., 2017)；晚白垩世生物大灭绝及大洋缺氧事件(OAE2)前夕，大陆风化强度增加，海水 δ^7Li 值显著降低(von Strandmann et al., 2013; Sun He et al., 2018)。然而，也有研究表明细粒级(<63 μm)沉积物中 δ^7Li 对气候变化不敏感，因此 δ^7Li 示踪大陆风化的可靠性还有待进一步证实。

2.2.4 Mg 同位素

Mg 有三个稳定同位素，即 ^{24}Mg(78.99%)、^{25}Mg(10.00%)和 ^{26}Mg(11.01%)，它们之间存在较大的相对质量差，如 ^{24}Mg 与 ^{26}Mg 之间相对质量差约达 8%，在地质作用过程中可以发生显著的 Mg 同位素质量分馏(Catanzaro et al., 1966；朱祥坤等，2013)。同时，Mg 不仅是地壳和地幔中的主量元素，也是主要的流体活动性元素，这决定了它在化学风化过程中会伴随明显的同位素分馏。已有研究表明，Mg 同

位素在化学风化过程中会产生高达 2‰的分馏,其中轻同位素^{24}Mg、^{25}Mg 更易随流体迁移,而重同位素^{26}Mg 不易被溶解迁移,保留在风化残余物中,导致风化残余物中具有高 δ^{26}Mg 值(图 4),搬运介质中具有低 δ^{26}Mg 值(Wimpenny et al., 2010a; Teng Fangzhen et al., 2010; von Strandmann et al., 2012; Liu Xiaoming et al., 2014),因此风化残余物中更高的 δ^{26}Mg 值指示了温暖湿润的气候条件,更低的 δ^{26}Mg 值则指示了寒冷干燥的气候条件(Huang Jinxiang et al., 2016)。

黏土矿物对不同同位素吸附能力差异可能也是导致风化过程中 Mg 同位素质量分馏的原因。Huang Kangjun 等(2012)、Liu Xiaoming 等(2014)对玄武岩风化剖面的研究显示高岭石、三水铝石优先吸附^{26}Mg,造成^{26}Mg 在风化残余物中的富集。Wimpenny 等(2014)对黏土矿物中不同赋存形态 Mg 同位素的测量结果表明,黏土矿物晶体结构中 Mg 同位素组成较重,黏土矿物表面和层间的 Mg 同位素组成较轻,黏土矿物吸附过程并不产生同位素分馏。可见,目前对风化作用过程中 Mg 同位素的分馏机制还不完全清楚,同时现有 Mg 同位素示踪大陆风化的研究集中于玄武岩、安山岩、花岗岩、碳酸盐岩等岩石风化剖面,还有待更深入和更广泛的研究。

2.2.5　K 同位素

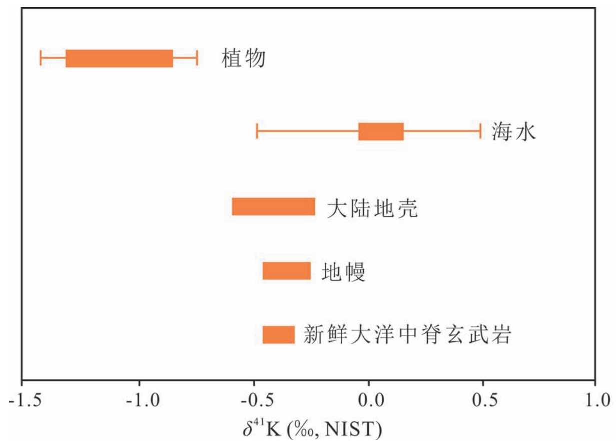
K 是地表河流和地壳中的主量元素,约 90%的河流溶解 K 来自于硅酸盐的风化(Meybeck, 1987; Berner and Berner, 2012),因此 K 稳定同位素(^{39}K 和^{41}K)可以示踪大陆硅酸盐风化。在硅酸盐风化过程中,轻 K 同位素优先迁移到水溶液中,河流溶解负荷 δ^{41}K 值降低,风化残余物具有较高的 δ^{41}K 值,河流溶解 K 同位素与风化强度负相关(图 5)(Hu Yan et al., 2020)。重 K 同位素随河流输入海洋造成海水 δ^{41}K 值的变化,因此,利用古海水 δ^{41}K 记录可以从地球历史的角度推断大陆风化强度(Hille et al., 2019; Teng Fangzhen et al., 2020)。

2.2.6　Cu 同位素和 Zn 同位素

Cu 和 Zn 均属于过渡金属元素。大陆风化作用是海洋 Cu 和 Zn 地球化学循环主要的“源”,风化过程中 Cu 和 Zn 分馏的可能原因包括: ① 主要造岩矿物的溶解过程发生同位素分馏; ② 溶解态以及次生矿物吸附态的同位素分馏;③ 大气浮沉的输入;④ 植物的吸收作用(Moynier et al., 2017)。

岩石氧化淋滤过程中,重 Cu 同位素被优先释放进入河流体系,进而注入海洋,造成河水和海水中相对较重的 Cu 同位素组成(图 6)。氧化淋滤过程对 Zn 同位素的分馏程度较低,水体中 Zn 同位素组成和原岩几乎一致(图 6),不会超过 0.1‰~0.3‰(Weiss et al., 2014)。Cu、Zn 同位素在示踪大陆风化强度方面的应用还较匮乏,关于大陆风化对 Cu 和 Zn 同位素分馏影响机制还不清楚。但是已有的研究(吕逸文,2018)证实在黑色页岩和碳酸盐岩的风化过程中,存在 Cu 和 Zn 同位素分馏现象,值得再做更加深入和广泛的研究。

上述研究表明,目前没有任何地球化学参数能够完全准确地示踪大陆风化强度,需要多参数结合,



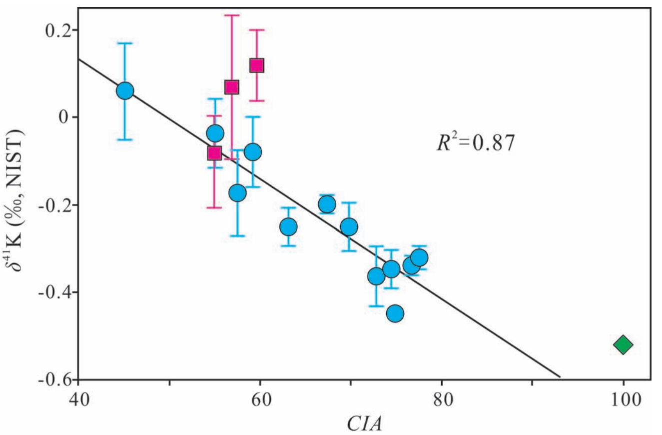


图 5 自然储库 δ^{41}K(引自 Hu Yan et al., 2020; Teng Fangzhen et al., 2020)以及河流沉积物中 δ^{41}K 与 *CIA* 关系(引自 Hu Yan et al., 2020)

Fig. 5 Potassium isotopic composition in natural reservoir (Hu Yan et al., 2020; Teng Fangzhen et al., 2020), and the plot of δ^{41}K vs. *CIA* (from Hu Yan et al., 2020)

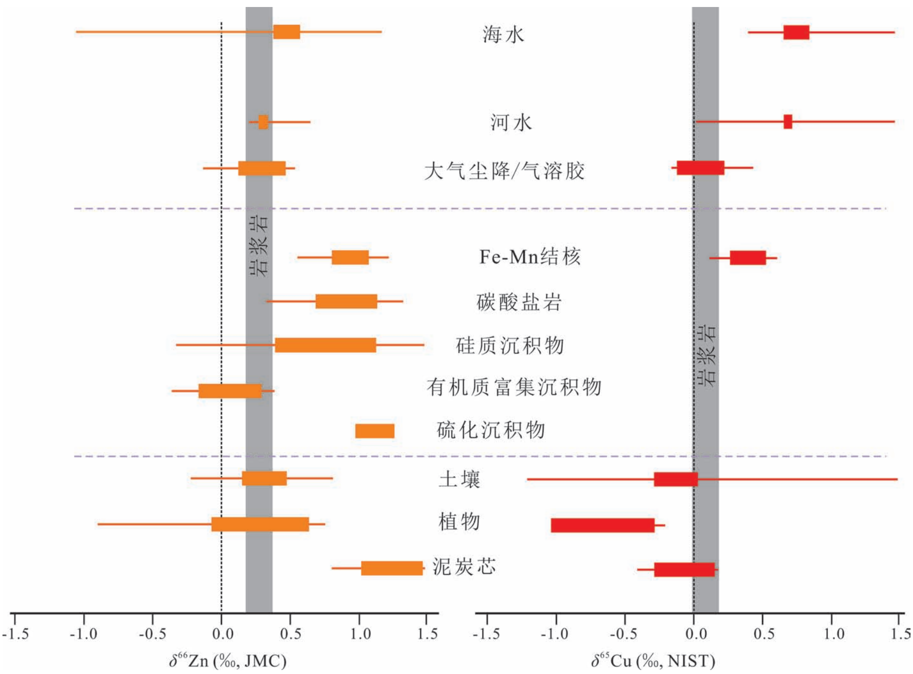


图 6 表生环境自然样品 Cu、Zn 同位素组成(引自 Moynier et al., 2017;吕逸文,2018)

Fig. 6 Copper and zinc isotopic composition in natural reservoir under supergene environment (from Moynier et al., 2017; Lü Yiwen et al., 2018&)

互相验证,才能保证解释结果的准确性。有研究显示 Tethyan 南部黏土矿物的分布与气候分带之间相关性非常明显,揭示黏土矿物的分布能够反映古气候和大陆风化特征(Chenot et al., 2018)。因此,矿物学与地球化学参数的有效结合,有望为大陆风化强度研究提供更可靠的手段。

3 扬子地区 E—C 转折期大陆风化作用

"雪球地球"理论认为在新元古代成冰纪结束后,距今 652.5 Ma 左右(邓俊等,2020,及该文中相关引用文献),地球迅速转入温室气候(Hoffman et al., 1998),E—C 转折期全球化学风化强烈(Shield, 2005)。然而有研究发现在埃迪卡拉纪晚期亦有冰期沉积物的存在,如我国华北的正目观组、罗圈组和凤台组(Le Heron et al., 2018;岳亮等,2020),以及西北的汉格尔乔克组和红铁沟组(Xiao Shuhai et al., 2004; Shen Bing et al., 2010)。在高纬度地区的爱沙尼亚(位于波罗的大陆,60°S),有研究发现其寒武纪早期黑色页岩样品的 *CIA* 值低至 59,指示寒冷干燥气候下较弱的化学风化作用(Tosca et al., 2010)。因此埃迪卡拉纪晚期—寒武纪早期可能并非长期处于稳定的超级温室气候环境中(Shen Bing et al., 2010;岳亮等,2020)。

对于我国华南扬子地区而言,其在埃迪卡拉纪晚期发育台内凹陷和大规模开放盆地,台地区发育灯影组白云岩,盆地区发育老堡组硅质岩(图 7a);早寒武世早期,全球海平面上升,碳酸盐台地遭到广泛淹没,到牛蹄塘沉积期形成以黑色细粒沉积为主的陆架环境(戴传固等,2013; Yeasmin et al., 2017)。快速海侵后保存了之前的地形地貌,黑色岩系在台地区直接不整合沉积于白云岩之上(图 7b),如上扬子台地区域灯影组顶部广泛发育有不整合面或岩溶面(朱东亚等,2014;杨雨等,2014;刘宏等,2015;丁一,2018),在盆地区则与下伏硅质岩呈整合接触(图 7c)。可见,扬子地区在 E—C 转折期经历了风化作用和快速海侵。近年来,我国扬子地区大陆风化强度研究已积累了一定的基础。前人通过对三峡地区与云南东部 E—C 地层序列的研究,发现在埃迪卡拉纪末期$n(^{87}Sr)/n(^{86}Sr)$显著增高并于 E—C 转折期附近达到最大值,而在进入寒武纪之后,$n(^{87}Sr)/n(^{86}Sr)$又逐渐减小(Sawaki et al., 2008, 2014; Li Da et al., 2013)。最近,Stammeier et al. (2019) 统计了全球各地 E—C 时期的$n(^{87}Sr)/n(^{86}Sr)$数据,同样发现了在 E—C 转折期$n(^{87}Sr)/n(^{86}Sr)$迅速增高,进入寒武纪又明显降低的变化规律。说明在 E—C 转折期大陆风化作用较为强烈,但可能存在明显的波动。Chen Can 等(2020)通过对三峡地区多个剖面的陡山沱组地层开展研究,系统地重建了埃迪卡拉纪末期 *CIA* 变化曲线,并识别出了三次 *CIA* 降低阶段,结合岩石矿物学、地球化学($n(^{87}Sr)/n(^{86}Sr)$, $\delta^{18}O$)指标指出这三次 *CIA* 的降低对应三次气候变冷事件。贵州铜仁道坨剖面埃迪卡拉系陡山沱组 *CIA* 值总体较高,位于 70~85 之间(图 8),指示其源区气候温暖湿润,化学风化程度较强,寒武系九门冲组下部(黑色页岩段)*CIA* 值降至 55~70,反映源区气候转为寒冷干

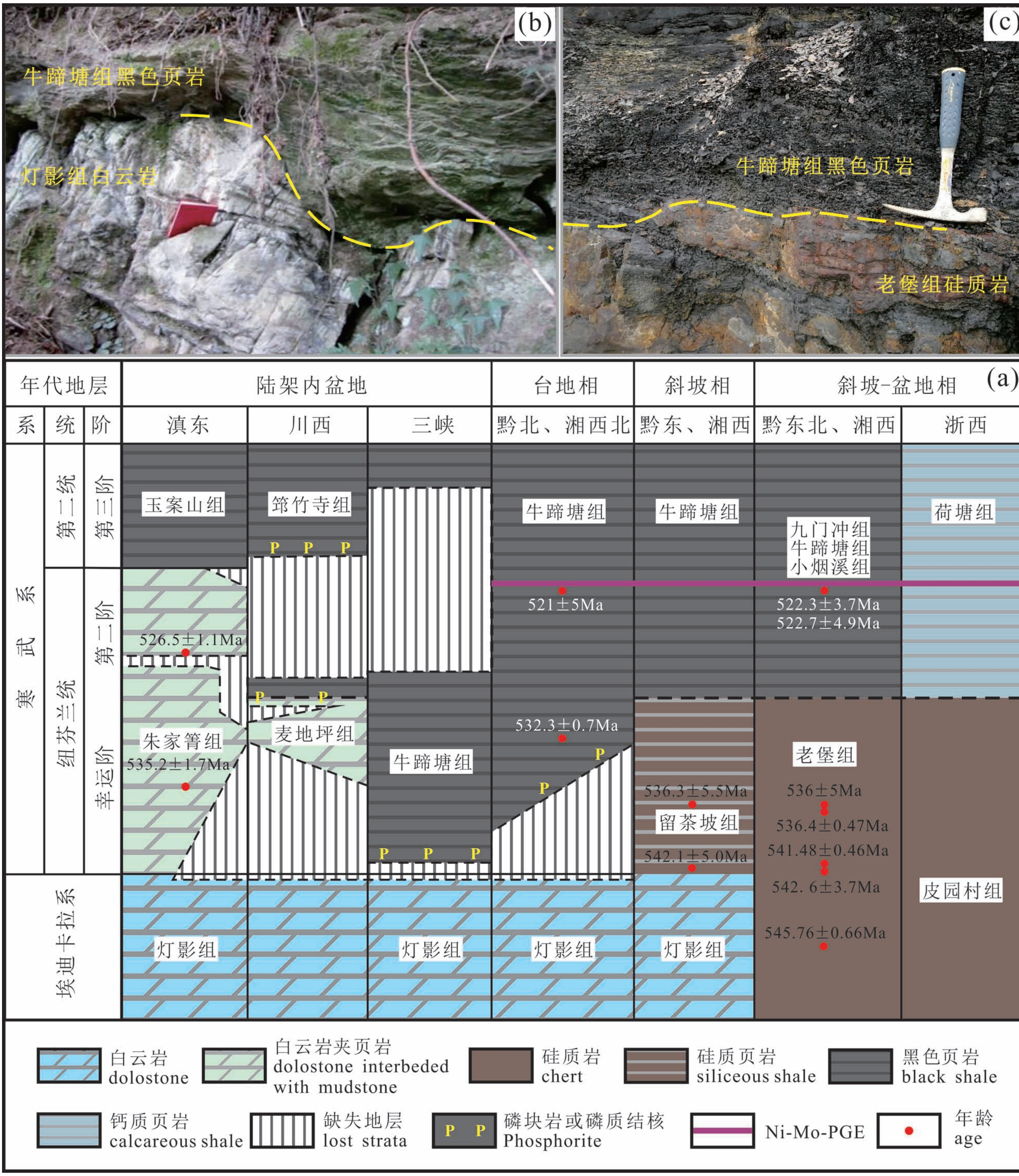


图 7 (a)扬子地区 E—C 转折期地层划分对比(改自陈建书等,2020;年龄数据来自朱日祥等,2009; Xu Lingang et al., 2011; Wang Xinqiang et al. ,2012; Zhu Bi et al. , 2013; Chen Daizhao et al. , 2016; Fu Yong et al. , 2016; Zhou Chuanming et al. , 2020);(b)灯影组与牛蹄塘组不整合接触,遵义松林;(c)老堡组与牛蹄塘组整合接触,铜仁

Fig. 7 (a) Stratigraphical division of E—C strata in Yangtze area (revised from Chen Jianshu et al. , 2020&, and age data are from Zhu Rixiang et al. , 2009&; Xu Lingang et al. , 2011; Wang Xinqiang et al. ,2012; Zhu Bi et al. , 2013; Chen Daizhao et al. , 2016; Fu Yong et al. , 2016; Zhou Chuanming et al. , 2020)

燥,风化作用以物理风化为主,而九门冲组上部 *CIA* 值再次升高,表明 E—C 转折期风化作用经历了强—弱—强的波动(Zhai Lina et al. , 2018)。另外有研究发现在道坨和坝黄剖面的牛蹄塘组底部,Ti/

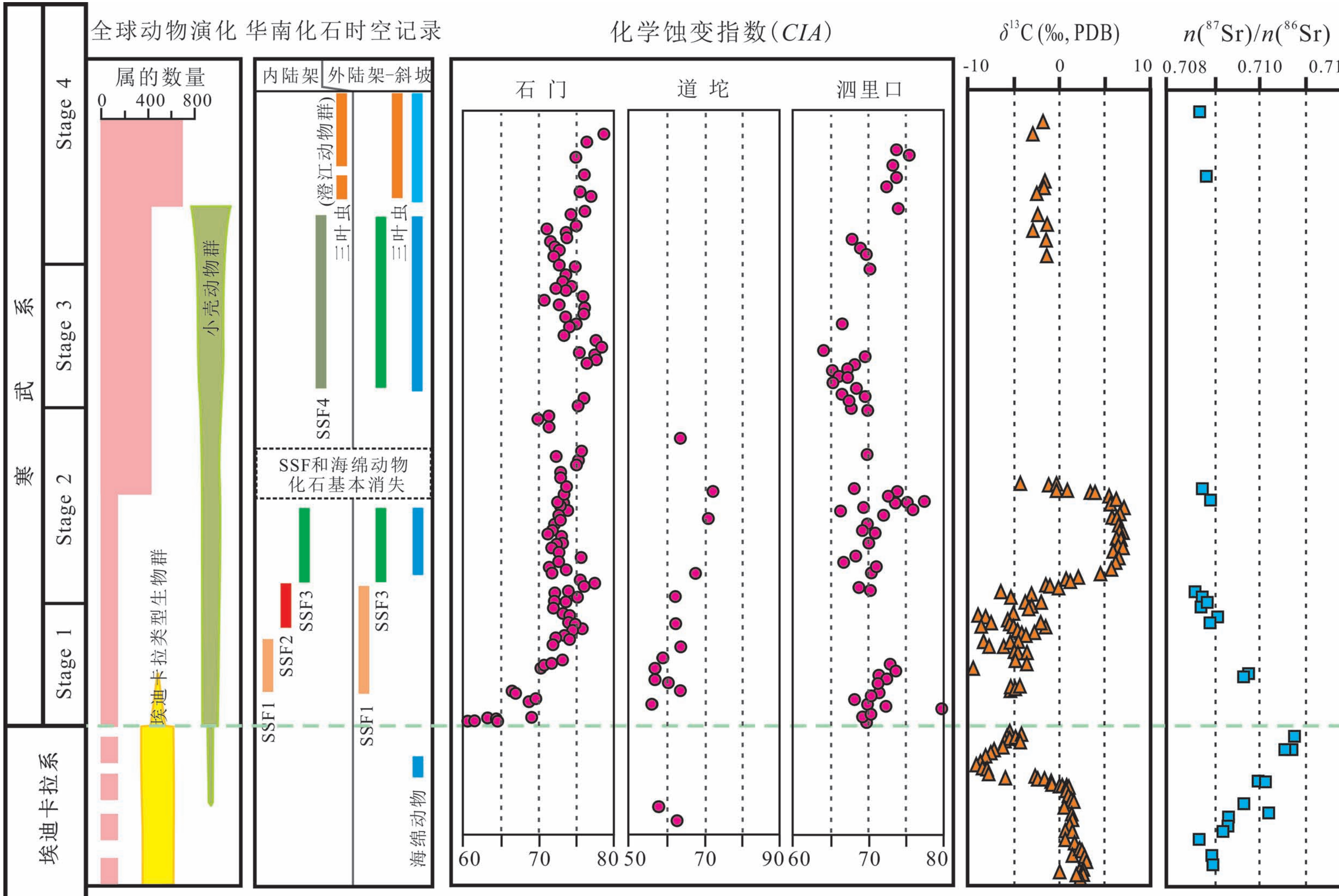


图8 扬子地区E-C转折期生命阶段性辐射和*CIA*、$n(^{87}Sr)/n(^{86}Sr)$、δ^{13}C同位素特征

Fig. 8 Characteristics of life radiation, *CIA*, $n(^{87}Sr)/n(^{86}Sr)$, and δ^{13}C of E-C strata in Yangtze area

全球动物演化参考Marshall, 2006；华南化石时空记录参考朱茂炎，2010，2019和金承胜，2014；δ^{13}C同位素引自Wei Guangyi et al., 2018；$n(^{87}Sr)/n(^{86}Sr)$引自Sawaki et al., 2008；道坨剖面*CIA*引自Zhai Lina et al., 2018；石门和泗里口剖面*CIA*引自张子虎，2018

Animals evolution is from Marshall. 2006; fossil record is from Zhu Maoyan et al., 2010&, 2019&, and Jin Chengsheng, 2014&; δ^{13}C is from Wei Guangyi et al., 2018; $n(^{87}Sr)/n(^{86}Sr)$ is from Sawaki et al., 2008; *CIA* data are from Zhai Lina et al., 2018, and Zhang Zihu, 2018&

Al 值增加且高于平均值,表明此时风尘输入增强,气候变得相对干燥(Yeasmin et al., 2017; Zhai Lina et al., 2018)。广西省三江县石门剖面和泗里口剖面清溪组页岩 *CIA* 值显示稳定的高值(76~84),指示寒武纪早期其源区中等至较强程度的化学风化作用,源区古气候条件以温暖湿润为主,与扬子陆块中部上斜坡(贵州东北部)源区存在显著差异,与同时期位于赤道附近的阿曼地区化学风化程度和古气候一致(张子虎,2018;熊晨,2019)。E—C 转折期碳酸盐岩 Nd 元素丰度和$\varepsilon_{Nd}(t)$值均显著降低,表明陆相风化物质向陆架海水的输出逐渐加强(Wei Guangyi et al., 2019)。考虑到不同剖面距离扬子或华夏板块的位置,Li Chao 等(2020)推测石门剖面和泗里口剖面主要记录了风化作用强烈的华夏板块的源岩信息,而靠近扬子一侧的道坨、硝滩、龙鼻嘴等剖面则反映了在 E—C 时期扬子区域的化学风化作用相对较弱,但具体造成化学风化强度不同的原因还不明晰,有待进一步探究。

现有示踪扬子地区 E—C 转折期大陆风化的地球化学证据不足,集中在$n(^{87}Sr)/n(^{86}Sr)$、$\delta^{13}C$、*CIA* 和$\varepsilon_{Nd}(t)$等,需要更多的地球化学参数来反映该风化作用的影响范围和演化特征,同时$n(^{87}Sr)/n(^{86}Sr)$、$\delta^{13}C$、*CIA* 和$\varepsilon_{Nd}(t)$等数据也局限在少数剖面和层段,如$\varepsilon_{Nd}(t)$仅涉及晚埃迪卡拉纪碳酸盐岩,缺少对早寒武纪黑色页岩的分析。风化作用与扬子地区古海洋环境、古生物演化和有机质富集等有什么影响?

大陆风化作用将大量离子、含氧盐以及惰性物质输入海洋,其中大量营养物质进入海洋会引发海水富营养化和海洋酸化,SO_4^{2-} 会氧化有机质产生 H_2S(硫酸盐还原作用),两方面因素导致海水缺氧、透光带降低,危及海洋生物的生存环境,这一效应积累到海洋生物所能承受的阈值后,会造成海洋生态系统的崩溃、生物的大量灭绝(Lenton and Watson, 2004; Riding and Liang, 2005; Yan Detian et al., 2010; Poulton et al., 2015; Sun He et al., 2018; Jin Chengsheng et al., 2020; Wei Guangyi et al., 2020)(图 9)。

风化作用将巨量营养盐输入海洋,促进生物生长,进而加速无机碳向有机碳的转化,提升海洋初始生产力(Lenton and Watson, 2004)。生物繁盛引起海洋富营养化,有机质降解消耗氧气,海水逐渐缺氧(Sun He et al., 2018),有利于有机质的保存,但也有研究表明生物繁盛会制造大量氧气,有利于海水中氧气浓度的增加(Gan Tian et al., 2021),这说明大陆风化对海洋环境的影响是多方面的,要准确认识这种影响,还需要更多相关研究的积累。风化作用将 SO_4^{2-} 等含氧盐输入海洋,SO_4^{2-} 氧化有机质产生

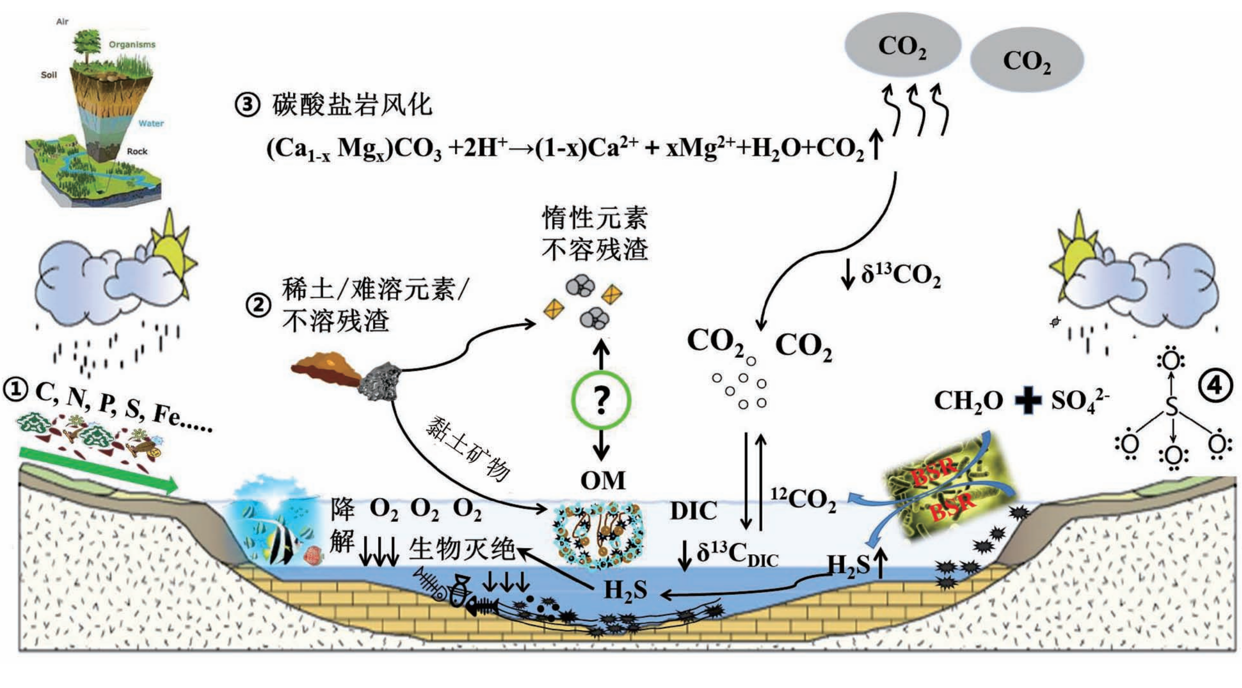


图 9 风化作用对海洋环境及有机质富集影响模式示意图(注:OM 为有机质;DIC 为溶解无机碳)

Fig. 9 Affecting pattern of continental weathering onmarine environment and organic matter enrichment (note: OM is organic matter; DIC is dissolved inorganic carbon)

H_2S,导致海洋环境逐渐转变为硫化环境,有助于保存有机质。然而,SO_4^{2-} 大量输入有助于减少对氧气的消耗,在浅水部位仍然保持相对较高的氧气浓度(He Tianchen et al., 2020)。风化作用带来大量黏土矿物,会吸附海水中的有机质(图 9),是有机质富集的重要因素之一(蔡进功等,2007;Cai Jingong et al., 2020)。在扬子地区 E—C 转折期黑色岩系中发现大量的有机黏土复合体(张慧等,2017),证实黏土矿物与有机质确实存在紧密的关系。但在不同的沉积相带内富集程度在时间和空间上具有明显的分异(有机质与黏土矿物主要聚集于斜坡相带),同时早寒武世有机碳同位素存在空间上的梯度差异($\delta^{13}C_{org}$ 值浅水相高,深水相低)(王新强等,2014),这些差异变化可能与陆源风化输入有关(Kennedy et al., 2006)。可见,风化作用对海洋中有机质的来源和保存都有较大的影响,最终影响有机质的富集。

扬子地区 E—C 转折期大陆风化对古海洋环境、有机质富集有何影响? 准确认识该问题有助于揭示古海洋环境演变和古生物演化规律,能为区内油气资源的勘探开发提供新的思路。

4 结论与展望

笔者等学习和总结了前人对扬子地区震旦纪(埃迪卡拉纪)—寒武纪(E—C)转折期大陆风化作用的研究成果,取得以下主要认识:

(1)扬子地区震旦纪(埃迪卡拉纪)—寒武纪(E—C)转折期遭受了较强烈的化学风化作用,在台地相区,牛蹄塘组黑色岩系不整合接触于灯影组白云岩之上,斜坡—盆地相区,该黑色岩系与下伏老堡组硅质岩呈整合接触。台地区不整合与 E—C 转折期全球“大不整合”具有紧密的关系,而盆地区发育的完整的沉积地层则记录了台地区被风化地层的痕迹。扬子地区 E—C 转折期兼具浅水台地和深水盆地环境,是研究这一时期全球大陆风化作用的重要窗口。

(2)现有扬子地区 E—C 转折期大陆风化的地球化学证据集中于$n(^{87}Sr)/n(^{86}Sr)$、$\delta^{13}C$、CIA 和$\varepsilon_{Nd}(t)$等,同时$n(^{87}Sr)/n(^{86}Sr)$、$\delta^{13}C$、CIA 和$\varepsilon_{Nd}(t)$等数据也局限在少数剖面和层段。因此迫切需要更多的地球化学参数来反映该风化作用的影响范围和演化特征。

(3)扬子地区 E—C 转折期大陆风化作用与海洋环境演变存在耦合关系,准确认识这种关系有助于揭示古生物演化、有机质富集的机制,能够为扬子地区油气资源勘探开发提供新思路。

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参 考 文 献 / References

(The literature whose publishing year followed by a “&” is in Chinese with English abstract; The literature whose publishing year followed by a “#” is in Chinese without English abstract)

蔡进功,包于进,杨守业,王行信,范代读,徐金鲤,王爱萍. 2007. 泥质沉积物和泥岩中有机质的赋存形式与富集机制. 中国科学(D 辑:地球科学),37(2):234~243.

陈建书,代雅然,唐烽,彭成龙,张嘉玮,朱和书,陈兴,王文明,龚桂源. 2020. 扬子地块周缘中元古代末—新元古代主要构造运动梳理与探讨. 地质论评,66(3):533~554.

戴传固,郑启钤,陈建书,王敏,张慧. 2013. 贵州雪峰—加里东构造旋回期成矿地质背景研究. 地学前缘,20(6):219~225.

邓俊,刘传朋,葛跃进,刘同,王凯凯. 2020. 新疆库鲁克塔格地区特瑞爱肯冰期下限及沉积物源分析. 地质论评,66(2):324~336.

丁一. 2018. 中上扬子东南缘晚震旦世灯影组沉积—构造格局. 导师:陈代钊. 北京:中国科学院大学博士学位论文:1~114.

冯连君,储雪蕾,张启锐,张同钢. 2003. 化学蚀变指数(CIA)及其在新元古代碎屑岩中的应用. 地学前缘,10(4):539~544.

付露露,肖益林,张兴亮,王洋洋,谭东波. 2020. Li 同位素组成对太古宙海水相关的表生环境过程的初步限定. 地球科学,DOI: 10.3799/dqkx.2020.108.

苟龙飞,金章东,贺茂勇. 2017. 锂同位素示踪大陆风化:进展与挑战. 地球环境学报,8(2):89~102.

金承胜,李超,彭兴芳,崔豪,石炜,张子虎,罗根明,谢树成. 2014. 华南寒武纪早期海洋化学状态的时空波动. 中国科学:地球科学,44(5):851~863.

李东永,肖益林,王洋洋,沈骥,刘海洋. 2019. 板块俯冲过程中的 Mg—Li—Fe—Cr 同位素分馏. 地球科学,44(12):4081~4085.

李明龙,杨波涌,郑德顺,陈林,田景春. 2021. 鄂西走马地区南华纪大塘坡间冰期古气候研究. 地质论评,67(1):39~55.

刘宏,罗思聪,谭秀成,李凌,连承波,曾伟,罗冰,山述娇. 2015. 四川盆地震旦系灯影组古岩溶地貌恢复及意义. 石油勘探与开发,42(3):283~293.

吕逸文. 2018. Cu 和 Zn 在大陆风化过程中的同位素分馏以及 Cu—Zn 同位素在古环境研究中的应用. 导师:李曙光,刘盛遨. 北京:中国地质大学(北京)博士学位论文:1~112.

王文倩,王伟,冯先翠,刘欣春,叶法丞,陈毅凤,刘静,陈孝政. 2014. 锶同位素地层学在海相地层划分和对比中的应用——以二叠纪乐平世海相碳酸盐岩地层为例. 地层学杂志,38(4):402~416.

王新强,史晓颖,Jiang Ganqing, 汤冬杰. 2014. 华南埃迪卡拉纪—寒武纪过渡期的有机碳同位素梯度和海洋分层. 中国科学:地球科学,44(6):1143~1154.

吴蓓娟,彭渤,张坤,匡晓亮,涂湘林,方小红,曾等志. 2016. 黑色页岩化学风化程度指标研究. 地质学报,90(4):818~832.

熊晨. 2019. 华夏陆块西缘震旦—寒武纪沉积物源分析及其构造古地理意义. 导师:陈洪德. 成都:成都理工大学博士学位论文:1~89.

徐小涛,邵龙义. 2018. 利用泥质岩化学蚀变指数分析物源区风化程度时的限制因素. 古地理学报, 20(3); 515~522.

杨雨,黄先平,张健,杨光,宋家荣,宋林珂,洪海涛,谭秀成,文龙. 2014. 四川盆地寒武系沉积前震旦系顶界岩溶地貌特征及其地

质意义. 天然气工业,34(3):38~43.
杨竞红,蒋少涌,凌洪飞,陈永权. 2005. 黑色页岩与大洋缺氧事件的 Re-Os 同位素示踪与定年研究. 地学前缘,12(2):143~150.
岳亮,刘自亮,Vandeginste V,马永生,陈洪德,张成见. 2020. 华北克拉通东南缘新元古代凤台组冰期沉积序列及演化. 地质论评,66(2):307~323.
张慧,焦淑静,林伯伟,郝临山,袁立颖. 2017. 扬子板块下寒武统页岩有机质与矿物质的成因关系. 天然气勘探与开发,40(4):25~33.
张文堂. 1997. 寒武纪生命扩张及澄江动物群的意义. 地学前缘,4(3~4):121~125.
张茜,肖渊甫,王晓飞,余谦,王剑,赵安坤,门玉澎,周业鑫. 2020. 四川盆地西南缘龙马溪组泥岩地球化学特征及物源区和构造背景分析. 地质论评,66(5):1393~1411.
张子虎. 2018. 华南寒武纪早期南华盆地东南缘深水区氧化还原状态时空波动及形成机制研究. 导师:李超. 武汉:中国地质大学(武汉)博士学位论文:1~97.
朱东亚,金之钧,张荣强,张殿伟,何治亮,李双建. 2014. 震旦系灯影组白云岩多级次岩溶储层叠合发育特征及机制. 地学前缘,21(6):335~345.
朱茂炎. 2010. 动物的起源和寒武纪大爆发:来自中国的化石证据. 古生物学报,49(3):269~287.
朱茂炎,赵方臣,殷宗军,曾晗,李国祥. 2019. 中国的寒武纪大爆发研究:进展与展望. 中国科学:地球科学,49(10):1455~1490.
朱日祥,李献华,侯先光,潘永信,王非,邓成龙,贺怀宇. 2009. 梅树村剖面离子探针锆石 U-Pb 年代学:对前寒武纪—寒武纪界线的年代制约. 中国科学 D 辑:地球科学,39(8): 1105~1111.
朱祥坤,王跃,闫斌,李津,董爱国,李志红,孙剑. 2013. 非传统稳定同位素地球化学的创建与发展. 矿物岩石地球化学通报,32(6):651~688.
Berner E K, Berner R A. 2012. Global Environment: Water, Air, and Geochemical Cycles. Princeton: Princeton Univ. Press.
Brantley S L, Megonigal J P, Scatena F N, Balogh-Brunstad Z, Barnes R T, Bruns M A, Van Cappellen P, Dontsova K, Hartnett H E, Hartshorn A S, Heimsath A, Herndon E, Jin L, Keller C K, Leake J R, McDowell W H, Meinzer F C, Mozdzer T J, Petsch S, Pett-Ridge J, Pregitzer K S, Raymond P A, Riebe C S, Shumaker K, Sutton-Grier A, Walter R, Yoo K. 2011. Twelve testable hypotheses on the geobiology of weathering. Geobiology, 9(2): 140~165.
Cai Jingong, Bao Yujin, Yang Shouye, Wang Xingxin, Fan Daidu, Xu Jin li, Wang Ai ping. 2007 #. Occurrence and enrichment mechanism of organic matter in argillaceous sediments and mudstones . Science China: Earth Science, 37(2): 234~243.
Cai Jingong, Zhu Xiaojun, Zhang Jingqiao, Song Mingshui, Wang Yongshi. 2020. Heterogeneities of organic matter and its occurrence forms in mudrocks: Evidence from comparisons of palynofacies. Marine and Petroleum Geology, 111:21~32.
Canfield D E, Poulton S W, Knoll A H, Narbonne G M, Ross G, Goldberg T, Strauss H. 2008. Ferruginous conditions dominated later Neoproterozoic deep-water chemistry. Science, 321(5891): 949~951.
Catanzaro E J, Murphy T J, Garner E L, Shields W R. 1966. Absolute isotopic abundance ratios and atomic weight of magnesium. J. Res. NBS A, 70: 453~458.
Chen Can, Wang Jiasheng, Wang Zhou, Peng Yongbo, Chen Xiaohong, Ma Xiaochen, Cen Yue, Zhao Jie, Zhou Peng. 2020. Variation of chemical index of alteration (CIA) in the Ediacaran Doushantuo Formation and its environmental implications. Precambrian Research, 347:105829; DOI: 10.1016/j.precamres.2020.105829
Chen Daizhao, Zhou Xiqiang, Fu Yong, Wang Jianguo, Yan Detian. 2016. New U-Pb zircon ages of the Ediacaran—Cambrian boundary strata in South China. Terra Nova, 27(1): 62~68.
Chen Jianshu, Dai Yaran, Tang Feng, Peng Chenglong, Zhang Jiawei, Zhu Heshu, Chen Xing, Wang Wenming, Gong Guiyuan. 2020&. Discussion on the Mesoproterozoic and Neoproterozoic major tectonic events in marginal area of the Yangtze Block. Geological Review, 66(3): 533~554.
Chenot E, Deconinck J F, Pucéat E, Pellenard P, Guiraud M, Jaubert M, Jarvis I, Thibault N, Cocquerez T, Bruneau L, Razmjooei M J, Boussaha M, Richard J, Sizun J P, Stemmerik L. 2018. Continental weathering as a driver of Late Cretaceous cooling: new insights from clay mineralogy of Campanian sediments from the southern Tethyan margin to the Boreal realm. Global and Planetary Change, 162: 292~312.
Cohen A S. 2004. The rhenium—osmium isotope system: Applications to geochronological and palaeoenvironmental problems. Journal of the Geological Society, 161: 729~734.
Dai Chuangu, Zheng Qiqian, Chen Jianshu, Wang Min, Zhang Hui. 2013&. A study on the metallogenic geological background of the Xuefeng—Caledonian tectonic cycle in Guizhou. Earth Science Frontiers, 20(6):219~225.
Deng Jun, Liu Chuanpeng, Ge Yuejin, Liu Tong, Wang Kaikai. 2020. The lower limit and provenance analysis of the Neoproterozoic Tereeken glaciation in Quruqtagh area, Xinjiang. Geological Review, 66(2): 324~336.
Ding Yi. 2018&. Tectonic—depositional pattern of the southeastern middle—upper Yangtze area during the late Edicaran Dengying Period. Tutor: Chen Daizhao. Beijing: Doctoral Dissertation of University of Chinese Academy of Science: 1~114.
Feng Lianjun, Chu Xuelei, Zhang Qirui, Zhang Tonggang. 2003&. Chemical alteration index (CIA) and its application in neoproterozoic clastic rocks . Earth Science Frontiers, (4):539~544.
Fike D A, Grotzinger J P, Pratt L M, Summons R E. 2006. Oxidation of the Ediacaran ocean. Nature, 444(7120): 744~747.
Fu Lulu, Xiao Yilin, Zhang Xingliang, Wang Yangyang, Tan Dongbo. 2020&. Preliminary determination of Li isotopic composition in epigenetic environmental processes related to Archean seawater. Earth Sciences, DOI: 10.3799/dqkx.2020.108.
Fu Yong, Dong Lin, Li Chao, Qu Wenjun, Pei Haoxiang, Qiao Wenlang, Shen Bing. 2016. New Re-Os isotopic constrains on the formation of the metalliferous deposits of the Lower Cambrian Niutitang formation. Journal of Earth Science, 27: 271~281.
Gan Tian, Luo Taiyi, Pang Ke, Zhou Chuanming, Wan Bin, Li Gang, Yi Qiru, Czaja A D, Xiao Shuhai. 2021. Cryptic terrestrial fungus-like fossils of the Early Edicaran Period. Nature Communications, 12(1): 641. https://doi.org/10.1038/s41467-021-20975-1.
Gou Longfei, Jin Zhangdong, He Maoyong. 2017&. Using lithium isotopes traces continental weathering: Progresses and challenges. Journal of Earth Environment, 8(2): 89~102.
He Tianchen, Jacopo D C, Newton R J, Wignall P B, Mills Benjamin J W, Simona T, Pietro D S, Turner E C, Jamieson R A, Vincenzo R, Manuel R, Jones R E, Dunhill A M. 2020. An enormous sulfur isotope excursion indicates marine anoxia during the end-Triassic mass extinction. Science Advances, 6(37): 1~8.

Henchiri S, Clergue C, Dellinger M. 2014. The influence of hydrothermal activity on the Li isotopic signature of rivers draining volcanic areas. Procedia Earth and Planetary Science, 10: 223～230.

Hille M, Hu Yan, Huang Tianyi, Teng Fangzhen. 2019. Homogeneous and heavy potassium isotopic composition of global oceans. Science Bulletin, 64(23), 1740～1742.

Hoffman P F, Kaufman A J, Halverson G P, Schrag D P. 1998. A Neoproterozoic snowball Earth. Science, 281: 1342～1346.

Hoffman P F, Li Zhengxiang. 2009. A palaeogeographic context for Neoproterozoic glaciation. Palaeogeography, Palaeoclimatology, Palaeoecology, 277(3～4): 158～172.

Holland H D. 1984. The Chemical Evolution of the Atmosphere and Ocean. Princeton: Princeton University Press.

Hu Yan, Teng Fangzhen, Plank T, Chauvel C. 2020. Potassium isotopic heterogeneity in subducting oceanic plates. Science Advances, 6: eabb2472.

Huang Jinxiang, Xiang Yuanxin, An Yajun, Griffin W L, Gréau Y, Xie Liewen, Pearson N J, Yu Huimin, O'Reilly S Y. 2016. Magnesium and oxygen isotopes in Roberts Victor eclogites. Chemical Geology, 438: 73～83.

Huang Kangjun, Teng Fangzhen, Wei Gangjian, Ma Jinlong, Bao Zhengyu. 2012. Adsorption- and desorption-controlled magnesium isotope fractionation during extreme weathering of basalt in Hainan Island, China. Earth and Planetary Science Letters, 359～360: 73～83.

Jenkyns H C, Jones C E, Gròcke D R, Hesselbo S P, Parkinson D N. 2002. Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. Journal of the Geological Society, London, 159: 351～378.

Jin Chengsheng, Li Chao, Thomas J. Algeo, Wu Shiyong, Cheng Meng, Zhang Zihu, Shi Wei. 2020. Controls on organic matter accumulation on the Early-Cambrian western Yangtze Platform, South China. Marine and Petroleum Geology, 111: 75～87.

Jin Chengsheng, Li Chao, Peng Xingfang, Cui Hao, Shi Wei, Zhang Zihu, Luo Genming, Xie Shucheng. 2014. Spatio-temporal fluctuation of marine chemical state in the Early Cambrian in south China. Science China: Earth Science, 44(5):851～863.

Kendall B, Creaser R A, Selby D. 2009. ^{187}Re-^{187}Os geochronology of Precambrian organic-rich sedimentary rocks. Geological Society, London, Special Publications, 326: 85～107.

Kennedy M, Droser M, Mayer L M, Pevear D, Mrofka D. 2006. Late Precambrian oxygenation; inception of the clay mineral factory. Science, 311: 1446～1449.

Kump L R, Barley M E. 2007. Increased subaerial volcanism and the rise of atmospheric oxygen 2.5 billion years ago. Nature, 448: 1033～1036.

Le Heron D P, Vandyk T M, Wu G H, Li M. 2018. New perspectives on the Luoquan Glaciation (Ediacaran—Cambrian) of North China. The Depositional Record, 4: 274～292.

Levasseur S, Birck J L, Allegre C J. 1999. The osmium riverine flux and the oceanic mass balance of osmium. Earth and Planetary Science Letters, 174: 7～23.

Lenton T M, Watson A J. 2004. Biotic enhancement of weathering, atmospheric oxygen and carbon dioxide in the Neoproterozoic. Geophysical Research Letters, 31: L05202.

Li Chao, Cheng Meng, Thomas J A, Xie Shucheng. 2015. A theoretical prediction of chemical zonation in early oceans (>520 Ma). Science China: Earth Science, 58 (11):1901～1909.

Li Chao, Love G D, Lyons T W, Fike D A, Sessions A L, Chu Xuelei. 2010. A stratified redox model for the Ediacaran ocean. Science, 328 (5974):80～83.

Li Chao, Zhang Zihu, Jin Chengsheng, Cheng Meng, Wang Haiyang, Huang Junhua, Algeo T J. 2020. Spatiotemporal evolution and causes of marine euxinia in the early Cambrian Nanhua Basin (South China). Palaeogeography Palaeoclimatology Palaeoecology, 546: 109676.

Li Da, Ling Hongfei, Shields-Zhou G A, Chen Xi, Cremonese L, Och L, Thirlwall M, Manning C J. 2013. Carbon and strontium isotope evolution of seawater across the Ediacaran—Cambrian transition: Evidence from the Xiaotan section, NE Yunnan, South China. Precambrian Research, 225: 128～147.

Li Dongyong, Xiao Yilin, Wang Yangyang, Shen Ji, Liu Haiyang. 2019. Mg—Li—Fe—Cr isotopic fractionation during subduction. Earth Science, 44(12): 4081～4085.

Li Meng, Vandyk T M, Wu Guanghui, Liu Wei, Heron D P L, Xiao Yang. 2020. A window into the Great Unconformity: Insights from geochemistry and geochronology of Ediacaran glaciogenic rocks in the North China Craton. Journal of Asian Earth Sciences, 194: 104327.

Ling Minglong, Tian Jingchun, Chen Lin, Xu Hui, Zheng Deshun, Liu Weiqing. 2019&. New zircon U-Pb age and its restriction on the warming time of the interglacial paleoclimate during the Cryogenian in the Yangtze Block. Journal of Geology, 127(6): 691～701.

Li Minglong, Yang Boyong, Zheng Deshun, Chen Lin, Tian Jingchun. 2021. Study on the paleoclimate during the Datangpo interglacial stage of the Nanhua Period in the Zouma area, western Hubei Province. Geological Review, 67(1): 39～55.

Li Weiping, Zheng Yongfei, Zhao Yanyan. 2017. Geochemical evidence from marine carbonate for enhanced terrigenous input into seawater during the Ediacaran—Cambrian transition in South China. Precambrian Research, 291: 83～97.

Li Weiping, Zhao Yanyan, Zhao Mingyu, Zha Xiangping, Zheng Yongfei. 2019. Enhanced weathering as a trigger for the rise of atmospheric O_2 level from the late Ediacaran to the early Cambrian. Scientific Reports, 9(1): 1～12.

Li Zhengxiang, Evans D A D, Halverson G P. 2013. Neoproterozoic glaciations in a revised global palaeogeography from the breakup of Rodinia to the assembly of Gondwanaland. Sedimentary Geology, 294: 219～232.

Linnemann U, Ovtcharova M, Schaltegger U, Gärtner A, Hautmann M, Geyer G, Vickers-Rich P, Rich T, Plessen B, Hofmann M, Zieger J. 2019. New high-re- solution age data from the Ediacaran—Cambrian boundary indicate rapid, ecologically driven onset of the Cambrian explosion. Terra Nova, 31: 49～148.

Liu Hong, Luo Sicong, Tan Xiucheng, Li Ling, Lian Chengbo, Zeng Wei, Luo Bing, Shan Shujiao. 2015&. Restoration of paleokarst geomorphology of Sinian Dengying Formation in Sichuan Basin and its significance, SW China. Petroleum Exploration and Development, 42(3): 283～293.

Liu Xiaoming, Teng Fangzhen, Rudnick R L, McDonough W F, Cummings M L. 2014. Massive magnesium depletion and isotope fractionation in weathered basalts. Geochimica et Cosmochimica Acta, 135: 336～349.

Lü Yiwen. 2018&. Cu and Zn isotope fractionation during continental weathering and the application of Cu and Zn isotopes in paleoceanography. Tutor: Li Shuguang, Liu Shengao. Beijing: Doctoral Dissertation of China University of Geosciences (Beijing): 1~112.

Lyons T W, Reinhard C T, Planavsky N J. 2014. The rise of oxygen in Earth′s early ocean and atmosphere. Nature, 506(7488): 307~315.

Mapstone N B, McIlroy D. 2006. Ediacaran fossil preservation: Taphonomy and diagenesis of a discoid biota from the Amadeus Basin, central Australia. Precambr. Res., 149: 126~148.

Markov G, Rogov V, Karlova G, Grazhdankin D. 2019. Taphonomic bias in Cloudina distribution data from Siberia. Estud. Geol., 75: 1~5.

Marschall H R. 2006. Explaining the cambrian "explosion" of animals. Earth and Planetary Science Letters, 34: 355~384.

Marschall H R, von Strandmann P A E, Seitz H M. 2007. The lithium isotopic composition of orogenic eclogites and deep subducted slabs. Earth and Planetary Science Letters, 262(3~4): 563~580.

Marshak S, Domrois S, Abert C, Larson T, Pavlis G, Hamburger M, Yang Xiaotao, Gilbert H, Chen Chen. 2017. The basement revealed: Tectonic insight from a digital elevation model of the Great Unconformity, USA cratonic platform. The Geological Society of America, 45(5): 391~394.

McArthur J M, Howarth R J, Shields G A. 2012. Strontium isotope stratigraphy. In: The Geological Time Scale. Waltham: Elsevier Science Ltd. 127~144. doi: 10.1016/B978-0-444-59425-9.00007-X

Medaris Jr L G, Driese S G, Stinchcomb G E, Fournelle J H, Lee S, Xu Huifang, DiPietro L, Gopon P, Stewart E K. 2018. Anatomy of a Sub-Cambrian Paleosol in Wisconsin: Mass Fluxes of Chemical Weathering and Climatic Conditions in North America during Formation of the Cambrian Great Unconformity. Journal of Geology, 126: 261~283.

Meybeck M. 1987. Global chemical weathering of surficial rocks estimated from river dissolved loads. Am. J. Sci., 287: 401~428.

McFadden K A, Huang Jing, Chu Xuelei, Jiang Ganqing, Kaufman A J, Zhou Chuanming, Yuan Xunlai, Xiao Shuhai. 2008. Pulsed oxidation and biological evolution in the Ediacaran Doushantuo Formation. PNAS, 105(9): 3197~3202.

Moynier F, Vance D, Fujii T, Savage P. 2017. The isotope geochemistry of zinc and copper. Reviews in mineralogy and geochemistry, 82(1): 543~600.

Nesbitt H W, Young G M. 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites: Nature, 299: 715~717.

Nesbitt H W, Young G M. 1989. Formation and diagenesis of weathering profiles: Journal of Geology, 97: 129~147.

Nielsen A T, Schovsbo N H. 2011. The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. Earth Sci. Rev., 107: 207~310.

Och L M, Shields-Zhou G A, Poulton S W, Manning C, Thirlwall M F, Li Da, Xi Chen, Ling Hongfei, Osborn T, Cremonese L. 2013. Redox changes in Early Cambrian black shales at Xiaotan section, Yunnan Province, South China. Precambrian Research, 225: 166~189.

Ohta T, Arai H. 2007. Statistical emperical index of chemical weathering in igneous rocks: A new tool for evaluating degree of weathering. Chemical Geology, 240: 280~297.

Palmer M R, Edmond J M. 1989. The strontium isotope budget of the modern ocean. Earth Planet. Sci. Lett., 92: 11~26.

Panahi A, Young G M, Rainbird R H. 2000. Behavior of major and trace elements (including REE) during Paleoproterozoic pedogenesis and diagenetic alteration of an Archean granite near Ville Marie, Quebec, Canada. Geochimica et Cosmochimica Acta, 64: 2199~2220.

Pegram W J, Krishnaswami S, Ravizza G E, Turekian K K. 1992. Record of seawater $^{187}Os/^{186}Os$ variation through the Cenozoic. Earth and Planetary Science Letters, 113: 569~576.

Penniston-Dorland S, Liu Xiaoming, Rudnick R L. 2017. Lithium isotope geochemistry. Reviews in Mineralogy & Geochemistry, 82: 165~217.

Peters S E, Gaines R R. 2012. Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion. Nature, 484: 363~366.

Poulton S W, Henkel S, M rz C, Urquhart H, Fl gel S, Kasten S, Damste J S S, Wagner T. 2015. A continental-weathering control on orbitally driven redox—nutrient cycling during Cretaceous Oceanic Anoxic Event 2. Geology, 43(11): 963~966.

Riding R, Liang L. 2005. Seawater chemistry control of marine limestone accumulation over the past 550 million years. Revista Espanola de Micropaleontologia, 37(1): 1~11.

Rooney A D, Selby D, Houzay J P, Renne P R. 2010. Re-Os geochronology of a Mesoproterozoic sedimentary succession, Taoudeni Basin, Mauritania: Implications for basin-wide correlations and Re-Os organic-rich sediments systematics. Earth and Planetary Science Letters, 289: 486~496.

Rooney A D, Chew D M, Selby D. 2011. Re-Os geochronology of the Neoproterozoic—Cambrian Dalradian Supergroup of Scotland and Ireland: Implications for Neoproterozoic stratigraphy, glaciations and Re-Os systematics. Precambrian Research, 185(3~4): 202~214.

Rudnick R L, Gao Shan. 2014. Composition of the continental crust. Treatise on Geochemistry. Waltham: Elsevier Science Ltd. : 1~64.

Sahoo Swapan K, Planavsky Noah J, Kendall Brian, Wang Xinqiang, Shi Xiaoying, Scott Clint, Anbar Ariel D, Lyons Timothy W, Jiang Ganqing. 2012. Ocean oxygenation in the wake of the Marinoan glaciation. Nature, 489(7417) 546~549.

Sawaki Y, Ohno T, Fukushi Y, Komiya T, Ishikawa T, Hirata T, Maruyama S. 2008. Sr isotope excursion across the Precambrian—Cambrian boundary in the Three Gorges area, South China. Gondwana Research, 14(1): 134~147.

Sawaki Y, Tahata M, Ohno T. 2014. The anomalous Ca cycle in the Ediacaran ocean: Evidence from Ca isotopes preserved in carbonates in the Three Gorges area, South China. Gondwana Research, 25(3): 1070~1089.

Scotese C R. 2016. PALEOMAP PaleoAtlas for GPlates and the PaleoData Plotter Program. 50th Annual GSA North—Central Section Meeting. doi: 10.1130/abs/2016NC-275387.

Shahakarami S, Buatois L A, Mangano M G, Hagadorn J W, Almond J. 2020. The Ediacaran—Cambrian boundary: Evaluating stratigraphic completeness and the Great Unconformity. Precambrian Research, 345: 105721.

Sharma M, Wasserburg G J. 1997. Osmium in the rivers. Geochimica et Cosmochimica Acta, 61: 5411~5416.

Shen Bing, Xiao Shuhai, Zhou Chuanming, Kaufman A J, Yuan Xunlai. 2010. Carbon and sulfur isotope chemostratigraphy of the Neoproterozoic Quanji Group of the Chaidam Basin, NW China: Basin stratification in the aftermath of an Ediacaran glaciation postdating the Shuram event? Precambrian Research, 177: 241~252.

Shields G A. 2005. Neoproterozoic cap carbonates: A critical appraisal of existing models and the plumeworld hypothesis. Terra Nova, 17 (4): 299~310.

Smith E F, Macdonald F A, Petach T A, Bold U, Schrag D P. 2015. Integrated stratigraphic, geochemical, and paleontological late Ediacaran to early Cambrian records from southwestern Mongolia. Geol. Soc. Am. Bull., 128: 442~468.

Smith E F, Nelson L L, Strange M A, Eyster A E, Rowland S M, Schrag D P, Macdonald F A. 2016. The end of the Ediacaran: Two new exceptionally preserved body fossil assemblages from Mount Dunfee, Nevada, USA. Geology, 44: 911~914.

Stammeier J A, Hippler D, Nebel O, Leis A, Grengg C, Mittermayr F, Kasemann S A, Dietzel M. 2019. Radiogenic Sr, stable C and O isotopes across Precambrian—Cambrian transition in marine carbonatic phosphorites of Malyi Karatau (Kazakhstan)——Implications for paleo-environmental change. Geochemistry, Geophysics, Geosystems, 20(1): 3~23.

Steinhoefel G, Brantley S L, Fantle M S. 2021. Lithium isotopic fractionation during weathering and erosion of shale. Geochimica et Cosmochimica Acta, 295: 155~177.

Sun He, Xiao Yilin, Gao Yongjun, Zhang Guijie, John F. Casey, Shen Yanan. 2018. Rapid enhancement of chemical weathering recorded by extremely light seawater lithium isotopes at the Permian—Triassic boundary. Proceedings of the National Academy of Sciences, 115 (15): 3782~3787.

Teng Fangzhen, Hu Yan, Ma Jinlong, Wei Gangjian, Roberta L R. 2020. Potassium isotope fractionation during continental weathering and implications for global K isotopic balance. Geochimica et Cosmochimica Acta, 278: 261~271.

Teng Fangzhen, Li Wangye, Rudnick R L, Gardner L R. 2010. Contrasting lithium and magnesium isotope fractionation during continental weathering. Earth and Planetary Science Letters, 300: 63~71.

Tomascak P B. 2004. Developments in the understanding and application of lithium isotopes in the earth and planetary Sciences. Review in Mineralogy & Geochemistry, 55: 153~195.

Tosca N J, Johnston D T, Mushegian A A, Rothman D H, Summons R E, Knoll A H. 2010. Clay mineralogy, organic carbon burial, and redox evolution in Proterozoic oceans. Geochimica et Cosmochimica Acta, 74: 1579~1592.

Tripathy G R, Hannah J L, Stein H J. 2018. Refining the Jurassic—Cretaceous boundary: Re-Os geochronology and depositional environment of Upper Jurassic shales from the Norwegian Sea. Palaeogeography, Palaeoclimatology, Palaeoecology, 503: 13~25. doi: 10.1016/j.palaeo.2018.05.005.

Verney-Carron A, Vigier N, Millot R. 2011. Experimental determination of the role of diffusion on Li isotope fractionation during basaltic glass weathering. Geochimica et Cosmochimica Acta, 75(12): 3452~3468.

von Strandmann P A E, Jenkyns H C, Woodfine R G. 2013. Lithium isotope evidence for enhanced weathering during Oceanic Anoxic Event 2. Nature Geoscience, 6: 668~672.

von Strandmann P A E, Opfergelt S, Lai Y J, Sigfússon B, Gislason S R, Burton K W. 2012. Lithium, magnesium and silicon isotope behaviour accompanying weathering in abasaltic soil and pore water profile in Iceland. Earth and Planetary Science Letters, 339~340: 11~23.

von Strandmann P A E P, Desrochers A, Murphy M J, Finlay A J, Selby D, Lenton T M. 2017. Global climate stabilisation by chemical weathering during the Hirnantian glaciation. Geochemical Prospectives Letters, 3(2): 230~236.

Wang Wei, Kano A, Okumura T, Ma Yongsheng, Matsumoto R, Matsuda N, Ueno K, Chen Xiaozheng, Kakuwa Y, Gharaie M, Ilkhchi M R. 2007. Isotopic chemostratigraphy of the microbialite-bearing Permian - Triassic boundary section in the Zagros Mountains, Iran. Chemical Geology, 244(3): 708~714.

Wang Wenqian, Wang Wei, Feng Xicui, Liu Xinchun, Ye Facheng, Chen Yifeng, Liu Jing, Chen Xiao zheng. 2014&. Application of strontium isotope stratigraphy in marine stratigraphic division and correlation——A case study of marine carbonate formations in the Leping, Permian. Journal of stratigraphy, 38(4): 402~416.

Wang Xinqiang, Shi Xiaoying, Jiang Ganqing, Zhang Wenhao. 2012. New U-Pb age from the basal Niutitang Formation in South China: Implications for diachronous development and condensation of stratigraphic units across the Yangtze platform at the Ediacaran—Cambrian transition. Journal of Asian Earth Sciences, 48:1~8.

Wang Xinqiang, Shi Xiaoying, Jiang Ganqing, Tang Dongjie. 2014#. Organic carbon isotope gradient and ocean stratification across the late Ediacaran-Early Cambrian Yangtze Platform. Science China: Earth Sciences, 44: 1142~1154.

Weiss D J, Boye K, Caldelas C, Fendorf S. 2014. Zinc isotope fractionation during early dissolution of biotite granite. Soil Science Society of America Journal, 78(78): 171.

Wen Hanjie, Fan Haifeng, Zhang Yuxu, Cloquet C, Carignan J. 2015. Reconstruction of Early Cambrian ocean chemistry from Mo isotopes. Geochimica et Cosmochimica Acta, 164: 1~16.

Wei Guangyi, Ling Hongfei, Shields G A, Chen Tianyu, Lechte M, Chen Xi, Qiu Chen, Lei Huanling, Zhu Maoyan. 2019. Long-term evolution of terrestrial inputs from the Ediacaran to Early Cambrian: Clues from Nd isotopes in shallow-marine carbonates, South China. Palaeogeography, Palaeoclimatology, Palaeoecology, 535: 109367.

Wei Guangyi, Planavsky N J, Tarhan L G, Chen Xi, Wei Wei, Li Da, Ling Hongfei. 2018. Marine redox fluctuation as a potential trigger for the Cambrian explosion. Geology, 56(7): 587~590.

Wei Guangyi, Wei Wei, Wang Dan, Li Tao, Yang Xiaoping, Shields G A, Zhang Feifei, Li Gaojun, Chen Tianyu, Yang Tao, Ling Hongfei. 2020. Enhanced chemical weathering triggered an expansion of euxinic seawater in the aftermath of the Sturtian glaciation. Earth and Planetary Science Letters, 539: 116244.

Wimpenny J, Gislason S R, James R H. 2010a. The behaviour of Li and Mg isotopes during primary phase dissolution and secondary mineral formation in basalt. Geochimica et Cosmochimica Acta, 74(18): 5259~5279.

Wimpenny J, James R H, Burton K W. 2010b. Glacial effects on weathering processes: New insights from the elemental and lithium isotopic composition of West Greenland rivers. Earth and Planetary Science Letters, 290(3~4): 427~437.

Wimpenny J, Colla C A, Yin Q Z. 2014. Investigating the behaviour of Mg isotopes during the formation of clay minerals. Geochimica et Cosmochimica Acta, 128: 178~194.

Wu Beijuan, Peng Bo, Zhang Kun, Kuang Xiaoliang, Tu Xianglin, Fang Xiaohong, Zeng Dengzhi. 2016&. Chemical weathering degree of black shale. Acta Geologica Sinica, 90(4): 818~832.

Xiao Shuhai, Bao Huiming, Wang Haifeng, Kaufman A J, Zhou Chuangming, Li Guoxiang, Yuan Xunlai, Ling Hongfei. 2004. The Neoproterozoic Quruqtagh Group in eastern Chinese Tianshan:

evidence for a post-Marinoan glaciation. Precambrian Research, 130: 1~26.

Xiong Chen. 2019&. Source Analysis of Sinian—Cambrian Sediments on the Western Margin of the Cathaysia Block and Its Tectonic and Paleogeographic Significance. Tutor: Chen Hongde. Chengdu: Doctoral Dissertation of Chengdu University of Technology: 1~89.

Xu Lingang, Lehmann B, Mao Jingwen, Qu Wenjun, Du Andao. 2011. Re-Os age of polymetallic Ni—Mo—PGE—Au mineralization in Early Cambrian black shales of South China——A reassessment. Economic Geology, 106: 511~522.

Xu Xiaotao, Shao Longyi. 2018&. Limiting factors in utilization of chemical index of alteration of mudstones to quantify the degree of weathering in provenance. Journal of Palaeogeography (Chinese Edition), 20(3): 515~522.

Yan Detian, Chen Daizhao, Wang Qingchen, Wang Jianguo. 2010. Large-scale climatic fl uctuations in the latest Ordovician on the Yangtze block, south China. Geology, 38(7): 599~602.

Yang Jinghong, Jiang Shaoyong, Ling Hongfei, Chen Yongquan. 2005&. Re-Os isotope tracing and dating of black shales and oceanic anoxic events. Earth Science Frontiers, 12(2): 143~150.

Yang Yu, Huang Xianping, Zhang Jian, Yuan Guang, Song Jiarong, Song Linke, Hong Haitao, Tan Xiucheng, Wen Long. 2014&. Eatures and geologic significances of the top Sinian karst landform before the Cambrian deposition in the Sichuan Basin. Natural Gas Industry, 34(3): 38~43.

Yao Weihua, Li Zhengxiang, Li Wuxian, Li Xianhua, Yang Jinhui. 2014. From Rodinia to Gondwanaland: A tale of detrital zircon provenance analyses from the Southern Nanhua Basin, South China. American Journal of Science, 314(1): 278~313.

Yeasmin R, Chen Daizhao, Fu Yong, Wang Jianguo, Guo Zenghui, Guo Chuan. 2017. Climatic—oceanic forcing on the organic accumulation across the shelf during the Early Cambrian (Age 2 through 3) in the mid—upper Yangtze Block, NE Guizhou, South China. Journal of Asian Earth Sciences, 134: 365~386.

Yue Liang, Liu Ziliang, Veerle V, Ma Yongsheng, Chen Hongde, Zhang Chengjian. 2020&. Glacial sedimentary sequence and evolution of the Fengtai Formation, southeastern margin of the North China Craton. Geological Review, 66(2): 307~323.

Zhai Lina, Wu Chaodong, Ye Yuntao, Zhang Shuichang, Wang Yizhe. 2018. Fluctuations in chemical weathering on the Yangtze Block during the Ediacaran—Cambrian transition: Implications for paleoclimatic conditions and the marine carbon cycle. Palaeogeography, Palaeoclimatology, Palaeoecology, 490: 280~292.

Zhang Hui, Jiao Shujing, Lin Bowei, Hao Linshan, Yuan Liying. 2017&. Genetic relationship between organic matter and minerals in the lower Cambrian shale of the Yangtze plate. Natural Gas Exploration and Development, 40 (4): 25~33.

Zhang Qian, Xiao Yuanfu, Wang Xiaofei, Yu Qian, Wang Jian, Zhao Ankun, Meng Yupeng, Zhou Yexin. 2020&. Geochemistry of the Longmaxi Formation mudstones of the southwest Sichuan Basin: Implications for provenance and source weathering. Geological Review, 66(5): 1393~1411.

Zhang Wentang. 1997&. Cambrian life expansion and the significance of chengjiang fauna. Earth Science Frontiers, 4(3~4): 117~121.

Zhang Xingliang, Shu Degan, Han Jian, Zhang Zhifei, Liu Jianni, Fu Dongjing. 2014. Triggers for the Cambrian explosion: Hypotheses and problems. Gondwana Research, 25(3): 896~909.

Zhang Yinggang, Yang Tao, Hohl S V, Zhu Bi, He Tianchen, Pan Wenqing, Chen Yongquan, Yao Xizhu, Jiang Shaoyong. 2020. Seawater carbon and strontium isotope variations through the late Ediacaran to late Cambrian in the Tarim Basin. Precambrian Research, 345: 105769; DOI: 10. 1016/j. precamres. 2020. 105769.

Zhang Zihu. 2018&. Spatiotemporal variations and formation mechanism of the marine redox conditions in the southeastern deep-water area of the Nanhua Basin (South China) in the Early Cambrian. Tutor: Li Chao. Wuhan: Doctoral Dissertation of China University of Geosciences (Wuhan): 1~97.

Zhou Chuanming, Huyskens M H, Lang Xianguo, Xiao Shuhai, Yin Qingzhu. 2019. Calibrating the terminations of Cryogenian global glaciations. Geology, 47(3): 251~254.

Zhou Chuanming, Huyskens M H, Xiao Shuhai, Yin Qingzhu. 2020. Refining the termination age of the Cryogenian Sturtian glaciation in South China. Palaeoworld, 29: 462~468.

Zhu Bi, Becker H, Jiang Shaoyong, Pi Daohui, Fischer-Godde M, Yang Jinghong. 2013. Re-Os geochronology of black shales from the Neoproterozoic Doushantuo Formation, Yangtze platform, South China. Precambrian Research, 225: 67~76.

Zhu Dongya, Jin Zhijun, Zhang Rongqiang, Zhang Dianwei, He Zhiliang, Li Shuangjian. 2014&. Characteristics and developing mechanism of Sinian Dengying Formation dolomite reservoir with multi-stage karst. Earth Science Frontiers, 21(6): 335~345.

Zhu Maoyan. 2010&. Origin of animals and Cambrian Explosion: Fossil evidence from China. Acta Palaeontologica Sinica, 49(3): 269~287.

Zhu Maoyan, Zhao Fangchen, Yin Zongjun, Zeng Han, Li Guoxiang. 2019&. Research on Cambrian explosion in China: progress and prospect. Science China: Earth Science, 49(10): 1455~1490.

Zhu Rixiang, Li Xianhua, Hou Xianguang, Pan Yongxin, Wang Fei, Deng Chenglong, He Huaiyu. 2009#. SIMS U-Pb zircon age of a tuff layer in the Meishucun section, Yunnan, southwest China: Constraint on the age of the Precambrian—Cambrian boundary. Science China: Earth Science, 39(8): 1105~1111.

Zhu Xiangkun, Wang Yue, Yan Bin, Li Jin, Dong Aiguo, Li Zhihong, Sun Jian. 2013&. Development of non-traditional stable isotope geochemistry. Bulletin of Mineralogy, Petrology and Geochemistry, 32(6): 651~688.

Continental weathering of Yangtze area during Edicaran (Sinian)—Cambrian transition stage: Advances and prospects

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Abstract: The researches of continental weathering, paleo-marine environment, and organic matter enrichment during Edicaran (Sinian)—Cambrian (E—C) transition stage in the Yangtze area, were organized and summarized in the present study. The results show that, during this stage, the Yangtze area suffered a strong chemical weathering, where includes carbonate platform facies and deep basin facies. The Early Cambrian Niutitang black shale lies with an unconformity upon the Edicaran Dengying dolomite in carbonate platform region, and this unconformity closely connected with the "Great Unconformity" during E—C transition stage around the word. However, in deep basin region, the Niutitang black shale conformably overlies on the Edicaran siliceous rock, and the complete E—C sedimentary strata has preserved weathering record of platform region. The existing geochemical evidences of continental weathering focus on $^{87}Sr/^{86}Sr$、$\delta^{13}C$、*CIA*, and $\varepsilon_{Nd}(t)$, and these geochemical data are limited to a few geological sections. Thus, more new geochemical factors are urgently needed to indicate the influence and evolution of the continental weathering during E—C transition stage. Finally, we suggest that an accurate understanding of coupling relationship between continental weathering and marine environment is significant for recognizing the evolution of life, and the enrichment of organic matter.

Keywords: Yangtze area; Edicaran—Cambrian transition stage; Sinian—Cambrian transition stage; Continental weathering; Marine environment; Organic matter

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