

鄂尔多斯盆地奥陶系锶同位素地球化学特征

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内容提要:对于鄂尔多斯盆地奥陶系碳酸盐岩锶同位素的研究主要集中于成岩作用识别与划分。本次以盆地中东部陕北坳陷镇钾1井马家沟组五段(以下简称马五段)以及盆地西缘桌子山地区三道坎组—桌子山组为研究对象,首次报道了未经成岩作用影响的碳酸盐岩的锶同位素数据,基于锶同位素地层学原理,试图恢复该沉积期古环境特征并对奥陶纪地层格架进行再讨论,共获得了如下几点认识:①镇钾1井马五段锶同位素自下而上以反复震荡,整体上略微增加为特征,震荡周期与蒸发岩韵律相吻合。桌子山地区三道坎组—桌子山组锶同位素以小幅波动为特征,整体上呈现出单调递减趋势。②马家沟组的地质年代归属于中奥陶世达瑞威尔中—晚期,而三道坎组—桌子山组的地质年代早于马家沟组,为中奥陶世达瑞威尔早—中期。③镇钾1井马五段处于局限台地—蒸发台地的沉积背景下,其锶同位素与全球演化曲线特征存在差异,说明了在该沉积背景下锶同位素对古环境变化反应更为敏感,能够成为区域古环境分析的重要指标。桌子山地区三道坎组—桌子山组由于处于开阔台地—缓坡的沉积背景下,与全球锶同位素演化曲线拟合度较高。为进一步研究鄂尔多斯盆地的沉积及构造差异提供了新依据,本次研究为全球锶同位素曲线提供了新的基础资料。

关键词:鄂尔多斯盆地;奥陶纪;锶同位素地层学;牙形石生物化石带

海相碳酸盐岩锶同位素主要有两种来源:一是富⁸⁷Sr的壳源物质,主要由大陆古老岩石风化通过河流向海水提供,全球平均值为0.7119 (Palmer et al., 1989)。二是贫⁸⁷Sr的洋中脊地幔物质,通过火山作用与海水发生物质交换,其平均值为0.7035 (Palmer et al., 1985)。海相碳酸盐岩锶同位素主要用于海平面变化、火山喷发事件、成岩作用类型、地层划分与对比、全球性地质事件、成岩流体、储层评价以及地层年代学的研究 (Burke et al., 1982; Popp et al., 1986; Tian Jingchun et al., 1995; Huang Sijing et al., 1997, 2002, 2004a, 2004b, 2005, 2006; Denison et al., 1997; Qing et al., 1998; Jiang Maosheng et al., 2002; Qin Jianhua et al., 2002; Huang Wenhui et al., 2006; Liu Cunge

et al., 2007; Wang Wenqian et al., 2013)。其中地层划分对比与年代学的研究是基于锶同位素地层学原理之上。由于锶在海水中的残留时间(大约 10^6 a)远大于海水混合时间(大约 10^3 a),且在海洋中的分布相对均匀,不受纬度、深度的影响,所以认为同时期海相碳酸盐岩地层中的锶同位素组成是相对一致且随地质年代的推移而发生变化 (Koepnick et al., 1985; Howarth et al., 1997; Veizer et al., 1999; McArthur et al., 2001; Huang Sijing et al., 2004a, 2006)。随着锶同位素数据日益丰富以及测试精度的提高,由此拟合的自显生宙以来各地质年代演化曲线也日益完善 (Montañez et al., 1996.; Ingram et al., 1994; Howarth et al., 1997; Denison et al., 1997; Jacobsen et al.,

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1999; McArthur et al., 2001)。通过已有的锶同位素数据结合演化曲线反演其形成的地质年代成为可能性并已经获得了许多喜人的成果(McArthur et al., 1994; Howarth et al., 1997; McArthur et al., 2001; Huang Sijing et al., 2002, 2004b; Pan Jiahua et al., 2002)。在国内,奥陶纪锶同位素的研究主要集中在塔里木盆地(Jiang Maosheng et al., 2002; Huang Sijing et al., 2004a, 2004c; Huang Wenhui et al., 2006; Yang Jiedong et al., 2012; Zhao Guowei, 2013),对于鄂尔多斯盆地奥陶系碳酸盐岩锶同位素的研究主要运用于成岩作用识别与划分(Huang Daojun et al., 2009; Su Zhongtang, 2011; Wang Lei, 2013; He Xunyun et al., 2014; Yang Xiyan et al., 2015),而在地层年代学方面的研究存在空缺。本次研究将以锶同位素地层学为原理,以前人拟合的锶同位素演化曲线为基础,结合研究区牙形石生物地层格架的相关成果,尝试对鄂尔多斯盆地西缘北段桌子山地区三道坎组—桌子山组以及中东部陕北坳陷镇钾1井马五段的地层年代进行标定。在此基础上,通过与塔里木板块和扬子板块同时期锶同位素曲线的对比,探讨不同沉积背景下锶同位素对古环境响应的差异。

1 区域地质概况

1.1 区域构造与地层

鄂尔多斯盆地位于华北板块西部,是一个稳定沉降、凹陷迁移、扭动明显的多旋回克拉通含油气盆地(Yang Junjie, 2002)。其北邻伊盟古隆起、东邻晋西挠褶带、南邻渭北隆起、西邻西缘逆冲带(图1)。鄂尔多斯盆地在奥陶纪共划分出西缘、南缘以及中东部三个地层单元,其中中东部地层单元是以中央隆起以东,渭北古隆起以北,晋西挠褶带以西为界线。在早古生代,鄂尔多斯盆地进入了稳定克拉通发育期,在多幕次快速海进和缓慢海退的海平面升降过程中,沉积了一套全区可追踪对比的寒武系、奥陶系海相碳酸盐岩夹碎屑岩沉积建造。

陕北坳陷镇钾1井位于中东部地层单元,在奥陶纪构造稳定,表现为陆表海碳酸盐台地沉积,奥陶系自下而上依次发育冶里组、亮甲山组和马家沟组。上部形成风化壳,缺失志留系—中石炭统,不整合面之上为本溪组碎屑岩沉积。

桌子山地区位于盆地西缘逆冲带,在奥陶纪被阿拉善地块、鄂尔多斯地块、古秦岭洋和古祁连洋所围限,所以呈南北向展布。该地区在早中奥陶世发

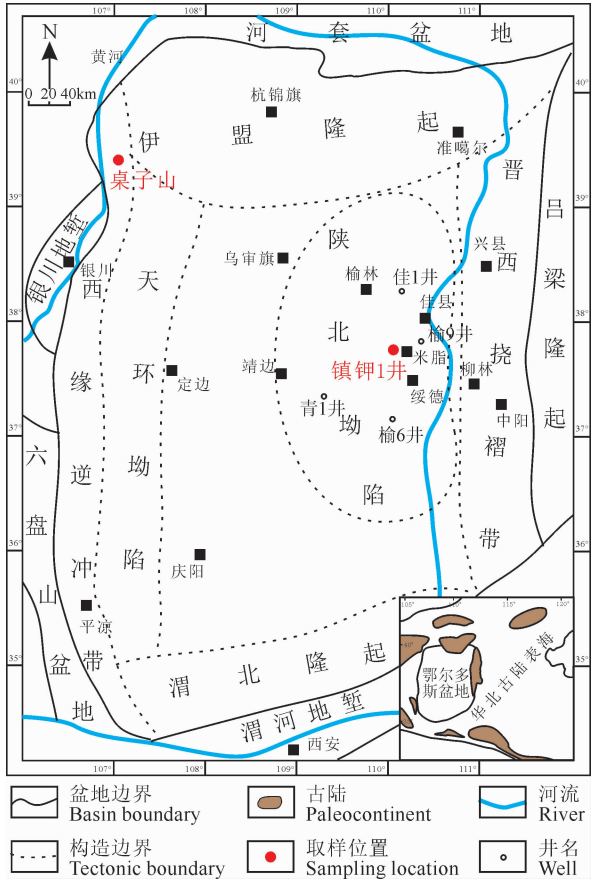


图1 鄂尔多斯盆地构造及取样位置图
(据刘群等,1997;张永生等,2014 修改)

Fig.1 Regional structure and sampling locations of Ordos basin (modified from Liu Qun et al., 1997; Zhang Yongsheng et al., 2014)

生了从被动大陆边缘向主动大陆边缘的构造背景转变(Yuan Weiguo et al., 1996; Qian Feng et al., 2002; Zhang Jin et al., 2004, 2012; Yan Quanren et al., 2009; Wu Sujuan et al., 2016)。奥陶纪以陆缘海—深水沉积为主,具有明显的“二元结构”,即下部发育台地相碳酸盐岩沉积,上部发育复理石沉积(Wang Zhentao et al., 2016)。自下而上依次沉积三道坎组、桌子山组、克里摩里组、乌拉力克组、拉什仲组、公乌素组和蛇山组。

1.2 岩石学特征

镇钾1井马家沟组岩性主要由碳酸盐岩与盐岩组成不等厚韵律层,夹少量石膏岩和白云质泥岩。根据岩性组合特征及垂向分布规律,可将马家沟组划分为马家沟组一段至六段(以下简称马一段—马六段),马五段自下而上可进一步划分为10个亚段(以下简称马五段1~10亚段)。其中马一段、马三段和马五段为蒸发岩段,而马二段、马四段和马六段

为蒸发岩段(淡化段)。马六段在研究区遭受剥蚀而零星发育。根据野外、钻井岩芯观察以及镜下显微鉴定,对马家沟组岩性进行如下划分:石灰岩类以泥晶石灰岩(图 2b)和颗粒石灰岩为主,在马二段、马四段最为发育,颗粒多以生物碎屑为主,鲕粒、藻团块、内碎屑等也较为常见,颗粒分选较差,亮晶方解石胶结,形成于开阔台地沉积环境。白云岩类(图

2d~g)在马一段、马三段、马五段海退时期发育,白云石常呈泥晶—细晶不等,常常与石膏伴生,石膏成结核状或纹层状。盐岩(图 2i)主要发育于马一段、马三段和马五段,呈粗晶状。石膏岩(图 2h)同样发育在各个海退期,往往呈揉皱状产出。

桌子山地区三道坎组与下伏寒武系阿不切亥组呈不整合接触。岩性主要为灰色中薄层石灰岩,夹

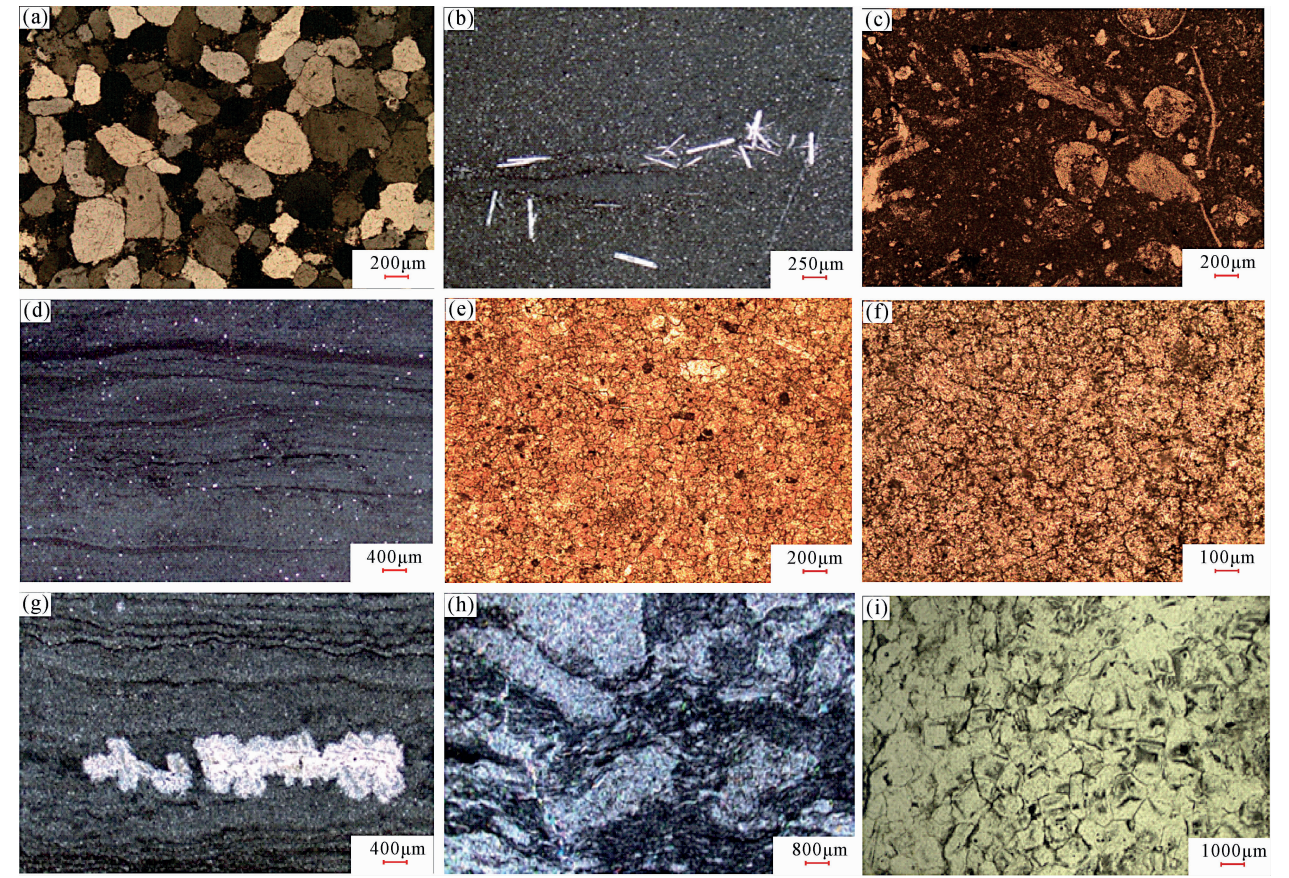


图 2 鄂尔多斯盆地奥陶系岩石类型及显微结构特征

Fig. 2 Rock type and microstructure characteristics of Ordovician in Ordos basin
(a)—石英砂岩,石英含量在 90%以上,几乎不含杂基,石英颗粒分选磨圆一般—较好,三道坎组,×50(+);(b)—泥晶石灰岩,零星分布针柱状石膏假晶,马家沟组二段,×40(-);(c)—颗粒石灰岩,颗粒为棘屑、介形虫、三叶虫等生物碎屑,碎屑含量可达到 40%~80%,基质为泥晶方解石,桌子山组,×50(-);(d)—准同生白云岩,发育泥质纹层,马五段,×25(-);(e)—砂屑白云岩,含少量砂屑颗粒,白云石发生了重结晶作用,三道坎组,×50(-);(f)—灰质白云岩,白云石晶体呈半自形,呈镶嵌式接触,由白云石交代方解石并重结晶形成,三道坎组,×100(-);(g)—石膏质白云岩,发生揉皱变形改造,马三段,×25(-);(h)—硬石膏岩,局部夹含膏泥晶白云岩,马五段,×12.5(-);(i)—白色粗晶盐岩,马五段,×10(-)
(a)—Quartz sandstone, quartz content accounts for over 90%, there is almost no matrix and quartz grains are normal-well sorted and grinded, Sandaokan Formation, ×50(+); (b)—micrite limestone with sporadic distribution of needle columnar gypsum pseudocrystals, the 2nd Member of Majiagou Formation, ×40(-); (c)—grainstone, grains include spicules, ostracoda and trilobites and accounts for 40% to 80%, the matrix is micritic calcite, Zhuozishan Formation, ×50(-); (d)—penecontemporaneous dolomite with argillaceous lamina, the 5th Member of Majiagou Formation, ×25(-); (e)—arenaceous dolomite containing a small amount of arenaceous particles, dolomite underwent recrystallization, Sandaokan Formation, ×50(-); (f)—calcite dolomite, dolomite crystal is semi-idiomorphic and in inlaid contact, it is formed by dolomite metasomatism and recrystallization, Sandaokan Formation, ×100(-); (g)—gypsic dolomite in crumpled deformation, the 3rd Member of Majiagou Formation, ×25(-); (h)—gypsum with few gypsic dolomicrite, the 5th Member of Majiagou Formation, ×12.5(-); (i)—white coarse-grained halite, the 5th Member of Majiagou Formation, ×10(-)

有紫红色中薄层石英粉砂岩(图 2a),偶可见砂质白云岩,粉砂岩中石英颗粒磨圆、分选较好,成熟度较高。该组向上陆源碎屑含量减少,主要发育在含砂云坪和局限台地的沉积环境中。桌子山组岩性以灰黑色中厚层泥粉晶石灰岩为主,夹少量中层状白云岩。石灰岩中可见泥质条带、燧石结核和含泥质、砂质团块。含藻类、头足类化石,种类数量丰富(图 2c),沉积环境为开阔台地。

2 样品与分析

2.1 样品制备与测试方法

本次研究的样品采集于鄂尔多斯盆地西缘和中东部。中东部的样品取自于陕北坳陷内镇钾 1 井岩芯,系统覆盖整个马五段。西缘桌子山地区老石旦剖面样品均匀分布并覆盖三道坎组上部和桌子山组。选取的样品除了 30 个成岩作用程度弱、矿物成分单一的碳酸盐岩样品外,还包含 6 个硫酸盐岩样品。最终共获得 36 组有效数据。

样品锶同位素测试分析在中国科学院南京土壤研究所完成。依据 JY/T004—1996《表面热电离同位素质谱方法通则》,选取的锶同位素标准物质为 NBS SRM 987,其 $^{87}\text{Sr}/^{86}\text{Sr}$ 值为 0.71034 ± 0.00026 。具体操作方法流程是:首先将样品粉碎至 200 目,取 100mg 粉末用 0.8mol/L 的盐酸溶于 Teflon 杯中。离心后的清液经过装有 AG 50W-X8 树脂的离子交换柱分离和纯化,以盐酸为淋洗剂,分离出纯净的 Sr,之后再在 VG354 同位素质谱仪上完成测试,误差用 2σ 表示。

主微量元素在核工业北京地质研究院实验室完成测试。检测过程依据 GB/T14506.28—2010《硅酸盐岩石化学分析方法-16 个主成分测定》。具体操作流程是:将样品粉碎至 200 目,在干燥处理后称取 700mg 与无水四硼酸锂熔融、以硝酸铵为氧化剂,加氟化锂和少量溴化锂作助熔剂和脱模剂,在熔样机上于 $1150 \sim 1250^\circ\text{C}$ 熔融,制成玻璃样片,在 X 射线荧光光谱仪上进行检测。

2.2 测试结果

马五段锶同位素样品包含泥晶石灰岩、泥晶白云岩和石膏。 $^{87}\text{Sr}/^{86}\text{Sr}$ 值介于 $0.708635 \sim 0.709190$ 之间,均值为 0.708865; Mn/Sr 值分布在 $0.022 \sim 0.757$ 之间,均值为 0.172; Sr 含量分布在 $0.185\% \sim 1.802\%$ 之间,均值为 0.884% 。三道坎组—桌子山组锶同位素样品包含泥粉晶石灰岩和生物碎屑石灰岩。 $^{87}\text{Sr}/^{86}\text{Sr}$ 值介于 $0.708872 \sim 0.709812$ 之间,

均值为 0.709361; Mn/Sr 值分布在 $0.090 \sim 0.643$ 之间,均值为 0.320; Sr 含量分布在 $0.275\% \sim 0.572\%$ 之间,均值为 0.390% 。其余测试结果如表 1 所示。

3 讨论

3.1 数据有效性分析

为了保证测试数据能够反映原始海水的信息,首先需要筛选出未受到成岩蚀变影响或受其影响较弱的样品。前人研究表明泥晶石灰岩是进行测试的最佳样品,在缺乏泥晶石灰岩的情况下生物碎屑石灰岩和泥晶白云岩也是较为理想的替代品 (Saltzman et al., 2000; Maloof et al., 2005; Kaljo et al., 2007; Ainsaar et al., 2010; Munnecke et al., 2010, 2011; Edwards et al., 2014)。本次研究的奥陶系马家沟组由于地质年代较老,会受到一定的成岩作用的影响。在样品选取上,岩性以泥晶石灰岩为主,首先通过镜下岩矿特征鉴定排除后期受到较强重结晶和交代作用的样品。

为了进一步确认样品成岩蚀变程度,前人通过实验总结出了以下地球化学判别指标:①常量元素,主要包含 Si、Al 和 Mg。Si 和 Al 主要来自于陆壳,对其含量的测定是为了评估在样品含有高 $^{87}\text{Sr}/^{86}\text{Sr}$ 陆源碎屑物质在溶解过程中对测试结果的影响。而 Mg 含量用于反映样品受白云化作用的强弱程度。②微量元素,主要包含 Mn/Sr 和 Sr 含量。海水中 Sr 含量远高于成岩流体和大气淡水,在碳酸盐埋藏或是表生成岩作用下会失去 Sr,所以 Sr 的含量越高,对原始海水信息的封存性越高。Derry et al. (1989) 和 Yang et al. (1999) 认为样品 Sr 含量大于 0.2% , 才能较好地代表海水。由于化学动力学效应,淡水相较于海水具有更高的 Mn 含量,如果不受到表生成岩作用的影响,海相碳酸盐岩的 Mn 含量会较低 (Huang Sijing, 1990)。此外, Kaufman et al. (1992) 通过锶、碳同位素反演古构造和古气候时总结出当 $\text{Mn}/\text{Sr} < 2 \sim 3$ 时,样品能够反映古海水特征。Huang Sijing et al. (2003) 同时也指出有一部分成岩作用也可能导致 Sr 含量的增加。本次测试样品中虽然包含硫酸盐岩(石膏岩),但是碳酸盐与硫酸盐的元素配分模式、沉积过程中矿物沉淀速度以及成岩作用中矿物重结晶速度都是类似的,所以评判碳酸盐岩成岩蚀变的指标同样可以运用到硫酸盐岩中 (Huang Sijing et al., 1990, 2006)。

表 1 鄂尔多斯盆地奥陶系主微量元素、锶同位素地球化学特征

Table 1 Geochemical characteristics of major, trace elements and Sr isotope of Ordovician in Ordos basin

样品编号	层位	岩性	Si(%)	Al(%)	Mg(%)	⁸⁷ Sr/ ⁸⁶ Sr	2σ(×10 ⁻⁶)	Mn/Sr	Sr(‰)
ZJ1-1	O ₂ m ₅	石膏	0.23	0.05	0.39	0.709034	9	0.027	1.488
ZJ1-2	O ₂ m ₅	石膏	2.16	0.48	0.73	0.709126	8	0.035	1.729
ZJ1-3	O ₂ m ₅	石膏	1.26	0.33	1.81	0.708802	8	0.039	1.025
ZJ1-4	O ₂ m ₅	泥晶白云岩	1.32	0.29	18.90	0.709190	5	0.757	0.185
ZJ1-5	O ₂ m ₅	泥晶石灰岩	0.80	0.20	2.03	0.708739	3	0.030	1.325
ZJ1-6	O ₂ m ₅	泥晶石灰岩	2.63	0.11	0.95	0.708929	8	0.186	0.269
ZJ1-7	O ₂ m ₅	泥晶石灰岩	7.31	0.59	2.95	0.708997	7	0.230	0.217
ZJ1-8	O ₂ m ₅	泥晶石灰岩	2.65	0.80	0.55	0.709068	6	0.216	0.185
ZJ1-9	O ₂ m ₅	泥晶石灰岩	2.37	0.26	1.65	0.708928	10	0.211	0.190
ZJ1-10	O ₂ m ₅	泥晶石灰岩	2.03	0.26	1.96	0.708829	11	0.208	0.192
ZJ1-11	O ₂ m ₅	石膏	0.81	0.16	2.58	0.708706	3	0.032	1.239
ZJ1-12	O ₂ m ₅	石膏	3.46	0.54	4.06	0.708949	2	0.036	1.112
ZJ1-13	O ₂ m ₅	泥晶白云岩	0.82	0.20	20.87	0.709031	5	0.478	0.230
ZJ1-14	O ₂ m ₅	石膏	1.45	0.33	0.76	0.708710	6	0.034	1.189
ZJ1-15	O ₂ m ₅	泥晶石灰岩	0.81	0.10	1.52	0.708651	9	0.029	1.391
ZJ1-16	O ₂ m ₅	泥晶白云岩	1.02	0.21	12.68	0.708717	14	0.571	0.578
ZJ1-17	O ₂ m ₅	泥晶白云岩	0.80	0.14	8.91	0.708737	3	0.114	1.049
ZJ1-18	O ₂ m ₅	泥晶石灰岩	0.73	0.30	3.78	0.708635	9	0.028	1.405
ZJ1-19	O ₂ m ₅	泥晶石灰岩	0.20	0.04	3.42	0.708648	4	0.022	1.802
ZZS-1	O ₂ s	泥粉晶石灰岩	3.72	0.92	0.65	0.709739	22	0.259	0.568
ZZS-2	O ₂ s	泥晶石灰岩	3.51	0.90	0.68	0.709718	19	0.643	0.446
ZZS-3	O ₂ s	泥粉晶石灰岩	3.41	0.83	1.88	0.709080	22	0.395	0.333
ZZS-4	O ₂ z	泥粉晶石灰岩	2.57	0.85	0.67	0.709206	24	0.228	0.442
ZZS-5	O ₂ z	泥粉晶石灰岩	1.19	0.40	2.72	0.709812	17	0.332	0.327
ZZS-6	O ₂ z	泥晶石灰岩	3.86	0.90	0.72	0.709691	20	0.262	0.296
ZZS-7	O ₂ z	泥晶石灰岩	2.02	0.29	0.65	0.709303	23	0.141	0.275
ZZS-8	O ₂ z	泥晶石灰岩	1.25	0.43	0.66	0.708872	19	0.137	0.282
ZZS-9	O ₂ z	生物碎屑石灰岩	1.31	0.34	0.75	0.709156	22	0.090	0.343
ZZS-10	O ₂ z	泥晶石灰岩	1.50	0.40	2.75	0.709488	20	0.113	0.411
ZZS-11	O ₂ z	生物碎屑石灰岩	3.14	0.57	0.74	0.709442	18	0.374	0.311
ZZS-12	O ₂ z	生物碎屑石灰岩	3.74	0.74	1.37	0.709156	21	0.248	0.438
ZZS-13	O ₂ z	泥晶石灰岩	5.52	0.75	0.57	0.709401	20	0.357	0.412
ZZS-14	O ₂ z	泥晶石灰岩	5.56	0.66	1.87	0.709234	20	0.568	0.464
ZZS-15	O ₂ z	生物碎屑石灰岩	13.46	1.10	0.69	0.709660	16	0.612	0.291
ZZS-16	O ₂ z	生物碎屑石灰岩	3.85	0.71	1.27	0.709085	17	0.298	0.572
ZZS-17	O ₂ z	泥晶石灰岩	2.58	0.58	0.69	0.709096	22	0.390	0.417

⁸⁷Sr/⁸⁶Sr-Si 交汇图(图 3a)显示除了 2 个样品含有相对较高的 Si 含量,其余样品 Si 含量均表现为低值,但镇钾 1 井样品 Si 含量整体略低于桌子山地区,此外桌子山地区的⁸⁷Sr/⁸⁶Sr 相较于镇钾 1 井普遍偏高。⁸⁷Sr/⁸⁶Sr-Al 交汇图(图 3b)表明所有样品的 Al 含量均处于低值,且⁸⁷Sr/⁸⁶Sr 未随着 Al 含量的增加而发生明显变化,两者具有较弱的相关性。除去镇钾 1 井 4 个具有高 Mg 含量的样品(泥晶白云岩)外,其余 Mg 含量介于 0.39%~4.06% 之间,均值为 1.51%,绝大部分样品 MgO 含量均低于 1%。说明后期白云化作用对样品的改造较为局限。根据 Sr 含量及 Mn/Sr 这两个指标,绘制了成岩蚀变程度判别图解(图 3c),共分为 I~V 五个区

域,从 I 至 V 成岩蚀变的程度不断增加。本次测试中,桌子山地区样品 Sr 含量普遍低于镇钾 1 井样品,其中共有 32 个样品达到了 Sr>0.2‰的判别标准,其余 4 个样品介于 0.185‰~0.192‰之间,也基本接近判别标准的下限。所有的样品均达到了 Mn/Sr<2~3 这一标准。整体上来看,大多数的样品均处于 I 区域,少量样品位于 I 和Ⅲ区域的交界处。此外,⁸⁷Sr/⁸⁶Sr 与 Mn/Sr 交汇图(图 3d)表明两者不存在明显的正相关性。综上分析,可以认为本次锶同位素测试的样品受到成岩蚀变的影响较为局限,其数据能够较好地反映原始海水信息。

3.2 海平面变化

由于壳源物质以及洋中脊热液混入的影响,导

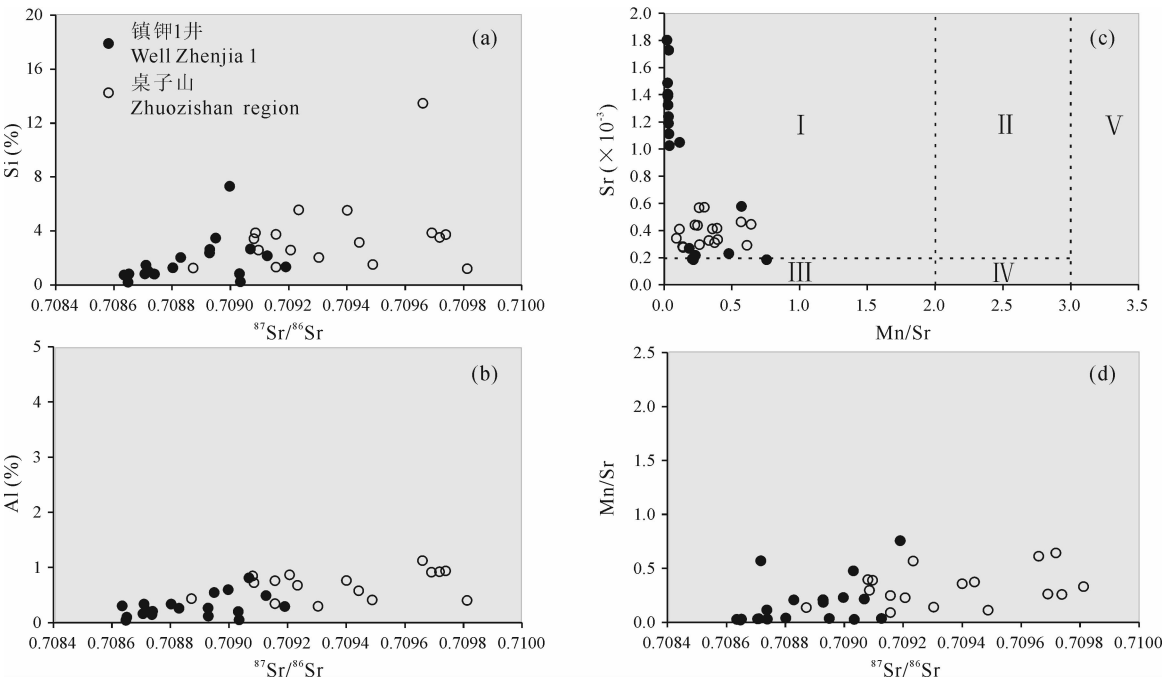


图 3 鄂尔多斯盆地奥陶系样品成岩蚀变程度判别图解

Fig. 3 Discrimination diagram of diagenetic alteration degree of Ordovician samples in Ordos basin

致海相碳酸盐岩与同期海水锶同位素值存在差异。许多学者在研究不同地质年代碳酸盐岩的锶同位素时,总结出锶同位素在海平面下降期其值会相应升高,而在海平面上升期会随之下降,即锶同位素与海平面的变化成负相关 (Arthur et al., 1985; Montañez et al., 1996)。运用该原理,可以通过碳酸盐岩锶同位素示踪海平面的变化。

镇钾 1 井马五段锶同位素演化曲线显示 (图 4): 马五段 7~10 亚段锶同位素总体呈下降趋势,表明该时期海平面持续的上升。直至马五段 6 亚段底部, Sr 同位素开始上升,并在该亚段一直保持相对高值,这是由于马五段 6 亚段为主要蒸发岩段,该段的海平面较低,并在沉积过程中混入了一定的壳源物质。随后,锶同位素再次出现震荡现象,震荡周期与蒸发岩韵律十分吻合,即淡化段 (马五段 5 亚段) 锶同位素为低值,蒸发段 (马五段 4 亚段) 锶同位素为高值。在马五段顶部 1~3 亚段,锶同位素出现了正漂移,这是由于加里东运动造成地层整体抬升,上奥陶统一中石炭统风化缺失,不整合面之下的碳酸盐岩受到大气淡水淋滤导致其值升高。综上所述,马五期锶同位素自下而上以反复震荡,总体上略微增加为特征。壳源物质的混入是主控因素,表明马五段沉积期海平面是反复升降的。

桌子山地区三道坎组—桌子山组沉积期锶同位

素虽然以小幅波动为特征 (图 5),但是整体上呈现出单调递减趋势,表明该沉积期海平面整体是不断上升的。这与前人对鄂尔多斯盆地海平面变化的认识一致 (Jia Zhenyuan et al., 1997; Liu Qun et al., 1997)。

3.3 锶同位素地质年代标定

在锶同位素地层学原理的基础上,对马五段地质年代进行再讨论。地质年代标定的准确性主要受到样品成岩蚀变程度、测试精度以及全球锶同位素演化曲线的影响。前两种因素前文已有相关叙述,认为样品可信度较高。本次选取的是 LOWESS 拟合锶同位素演化曲线 (McArthur et al., 2001)。这是到目前为止,国际上最为完整、最能反映海水信息的奥陶系锶同位素演化曲线,也是奥陶系海相地层定年、评价成岩流体对海相碳酸盐锶同位素组成影响最为重要的基础资料 (Huang Sijing et al., 2004a)。其奥陶系部分锶同位素值介于 0.7077~0.7092 之间 (图 6)。

可见,全球奥陶系锶同位素变化总趋势是单调下降,在中奥陶统下降幅度相对较大。学者们对国内奥陶系的研究表明海相碳酸盐的锶同位素变化也具有相同的规律 (Denison et al., 1997; Qing et al., 1998; Qin Jianhua et al., 2002; Huang Wenhui et al., 2006)。Jiang Maosheng et al. (2002) 还指出锶

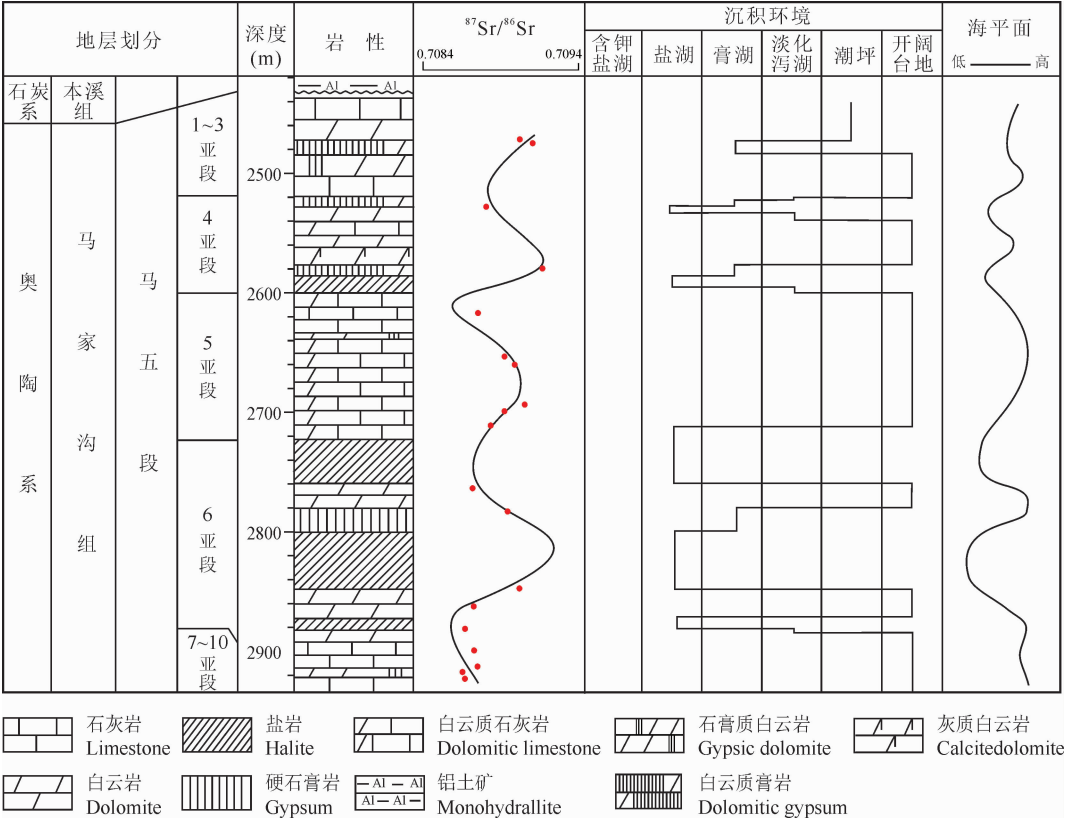


图 4 鄂尔多斯盆地中东部奥陶系马五段锶同位素综合柱状图

Fig. 4 Comprehension diagram of Sr isotope in the 5th Member of Majiagou Formation, mid-east of Ordos basin

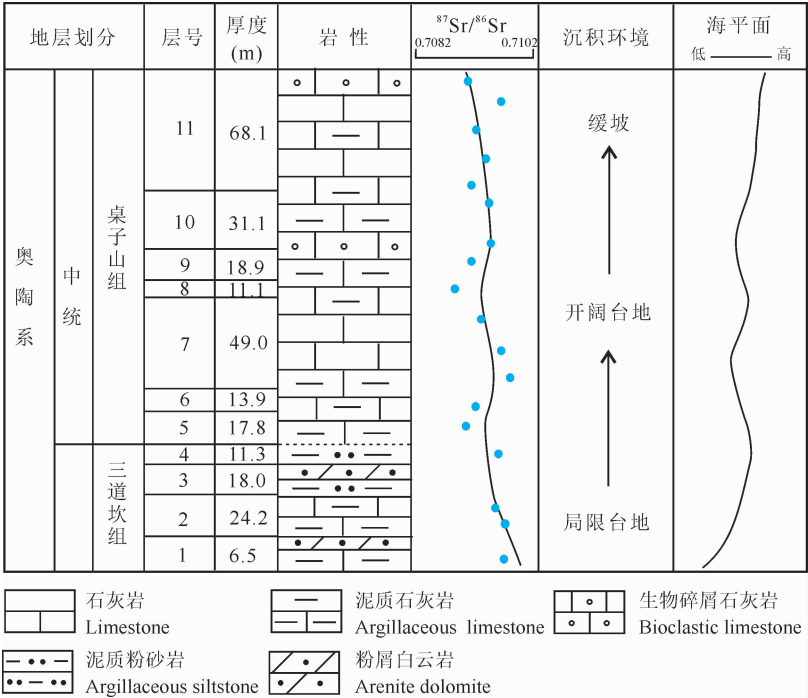


图 5 鄂尔多斯盆地西缘奥陶纪锶同位素综合柱状图

Fig. 5 Comprehension diagram of Sr isotope in Ordovician, west margin of Ordos basin

同位素从晚寒武世已经开始下降,并一直持续到距今大约 440 Ma 的奥陶世末。以上结论与人们对鄂尔多斯盆地海平面变化的认识一致。奥陶系内部的界线划分根据国际地层委员会

2018 年最新国际年代地层表。将所有样品铈同位素值投至奥陶纪铈同位素演化曲线上(图 6),镇钾 1 井马五段样品显示出除去马家沟组顶部受到大气淡水淋滤的 3 个样品以外,其余 16 个样品中有 13 个样品的铈同位素值位于中奥陶统,其中 2 个样品处于中奥陶统大坪阶(467.3Ma 和 469.8Ma),11 个样品处于中奥陶统达瑞威尔阶(年龄标定范围为 461.7~466.5Ma);而老石旦剖面三道坎组一桌子山组样品由于受到砂岩薄夹层的影响,其铈同位素值整体上呈现出正漂移且相较于马五段偏高,其中仅有 4 个样品的铈同位素值处于奥陶纪,1 个样品位于中奥陶世达瑞威尔期(465.1Ma),3 个样品位于早奥陶世(年龄标定范围为 476.7~480.2Ma),其余样品的铈同位素值都超出了 McArthur et al. (2001)拟合的铈同位素曲线范围。因此运用铈同位素标定三道坎组一桌子山组地质年代的方法可信度较低,但铈同位素地层学适用于镇钾 1 井马五段。

3.4 牙形石生物地层

3.4.1 镇钾 1 井

在镇钾 1 井岩芯的基础上,建立了奥陶纪牙形石生物化石带,这为地层年代标定与对比提供了可靠的古生物证据。自下而上可共划分出 *Tangshanodus tangshanensis* 带、*Plectodina onychodonta* 带和 *Aurilobodus serratus* 带等 3 个牙

形石带。马家沟组牙形石化石数量较少,属种比较单调,特征与华北板块基本相同,为北美中大陆(温暖型)牙形石动物群。Xing Enyuan et al. (2014)对牙形石属种的分布进行了具体划分。

Tangshanodus tangshanensis 带分布于镇钾 1 井马二段,以大量出现 *T. tangshanensis*, *S. flexilis* 等为特征。可对比于 An Taixiang et al. (1990)于华北板块下马家沟组建立的 *Tangshanodus tangshanensis* 带并归属为中奥陶世大坪期。直至 Wang Zhihao et al. (2014,2016)在奥陶系北庵庄组发现 *Histiodella Holodentata* 后,建立了 *Histiodella Holodentata*-*Tangshanodus tangshanensis* 带,并自上而下划分出 *Rhipidognathus laiwuensis* 和 *Rhipidognathus Maggolensis* 两个亚带,其中 *Rhipidognathus laiwuensis* 亚带对应原先的 *Tangshanodus tangshanensis* 带,时代为中奥陶世达瑞威尔中期。

Plectodina onychodonta 带分布于镇钾 1 井马四段一马五段 5 亚段。该带可与华北地台上马家沟组中段顶部至上段的 *Plectodina onychodonta* 牙形石带对比,其底界与顶界分别以 *Plectodina onychodonta* 和 *Aurilobodus serratus* 的首次出现为标志。Wang Zhihao et al. (2014)进一步完善了牙形石带的划分,在马家沟组上部建立了

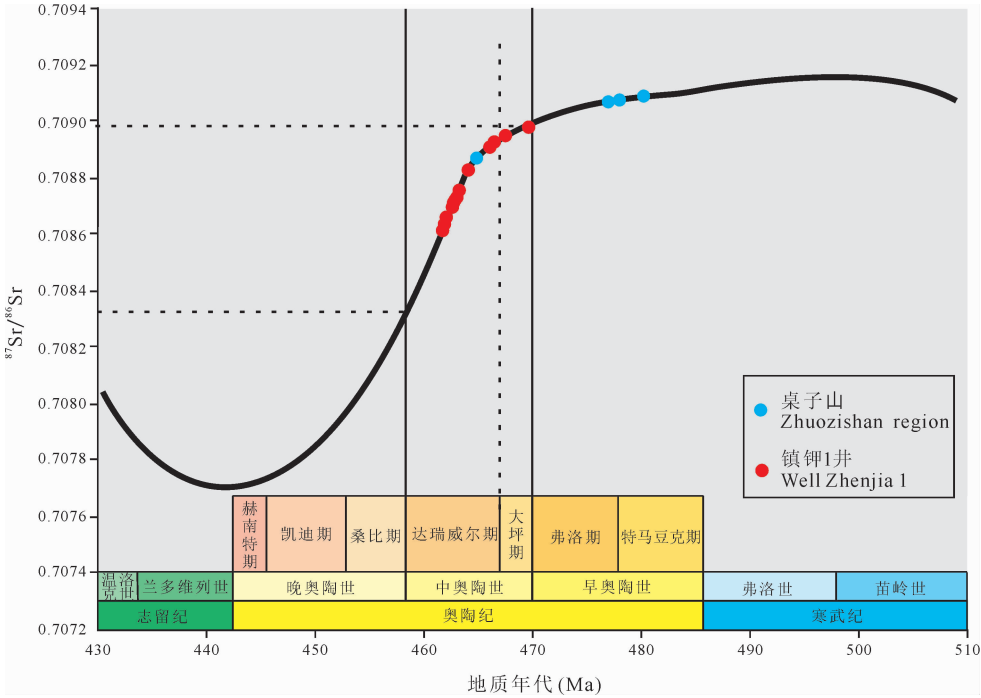


图 6 全球奥陶纪海水铈同位素演化曲线及鄂尔多斯盆地铈同位素年龄标定(据 McArthur et al. , 2001)
Fig. 6 Ordovician evolution curve of Sr isotope and age assignments in Ordos basin (revise after McArthur et al. , 2001)

Eoplacognathus suecicus 带,并自上而下划分出 *Plectodina onychodonta* 和 *Acontiodus? Linxiensis* 亚带。此处的 *Plectodina onychodonta* 亚带对应于 An Taixiang(1983)提出的 *Plectodina onychodonta* 带。其地质年代归属于中奥陶世达瑞威尔期中晚期。

Aurilobodus serratus 带分布于镇钾 1 井马五段 5 亚段。由 An Taixiang(1983)于山东莱芜上马家沟组建立,其下界以 *Aurilobodus serratus* 的首次出现为标志,上界不清。此带可以与华南扬子区 *Pygodus erra* 带的下部相对比。Wang Zhihao et al. (2014) 认为该带已经包括在 *Eoplacognathus suecicus* 带上部的 *Plectodina onychodont* 亚带之内,时代为中奥陶世达瑞威尔期晚期。

3.4.2 桌子山地区

Jing et al. (2016)通过对桌子山地区中奥陶统牙形石生物地层的研究,自三道坎组上部至桌子山组顶部共识别出 3 个牙形石生物化石带。自下而上依次为 *Histiodella cf. holodentata* 带, *Histiodella Kristinae* 带和 *Histiodella bellburnensis* 带。

Histiodella cf. holodentata 带以 *H. cf. holodentata* 的出现为特征 (Ethington et al., 1982) 并伴生 *Ansella crassa* 等 8 类牙形石属种。其顶底分别以 *Histiodella cf. holodentata* 和 *Histiodella Kristinae* 的首次出现为界限。该带分布于三道坎组上部—桌子山组底部,其地质年代归属于达瑞威尔中期。

Histiodella Kristinae 带共识别出 24 类牙形石属种,其中 *Histiodella Kristinae*、*Aurilobodus leptosomatus* 和 *Loxodus dissectus* 被认为最重要生物地层划分的依据。该牙形石带的顶底分别以 *H. kristinae* 和 *H. bellburnensis* 的首次出现为界限。该带分布于桌子山组中部,其地质年代归属于达瑞威尔中期。

Histiodella bellburnensis 带以 *Histiodella bellburnensis* 的分布范围作为划分依据。该带位于桌子山组中上部,Stouge (2012) 和 Serra et al. (2015) 认为该带归属于达瑞威尔中期。

值得注意的是, Jing et al. (2016) 在桌子山剖面顶部未划分牙形石生物化石带,但是在其对卧龙岗剖面的研究表明桌子山组上部克里莫里组的地质年代为达瑞威尔中期 (Jing et al., 2015)。由此可见,整个三道坎组上部至桌子山组也同样处于达瑞威尔中期。

3.5 地质年代归属

3.5.1 马家沟组

鄂尔多斯盆地中东部马家沟组地质年代的归属还没有达到共识。前人对于该地区奥陶系的划分虽有相似之处,但仍存在差异。Wang Xiaofeng et al. (1996) 认为马家沟组整体处于早奥陶世,上部为中奥陶统平凉组。Liu Qun et al. (1997) 认为马一段—马五段归属于中奥陶统,而马六段属于上奥陶世; Feng Zengzhao (1998) 认为马一段—马六段均属于中奥陶统,下部为下奥陶统亮甲山组; Fu Jinhua et al. (2001) 认为马一段—马六段均属于中奥陶统,且中奥陶统未发生地层缺失; Chen Anqing (2010) 认为马家沟组一段—六段均属于下奥陶统; Guo Yanru et al. (2014) 认为马五段对应中奥陶统大坪阶—达瑞威尔阶底部; Zhao Zhenyu et al. (2015) 认为马一段—马三段属于下奥陶统弗洛阶,马四段—马五段划分至中奥陶统大坪阶,上部地层缺失。可见,其争议主要集中在马家沟组所处中、下奥陶统界线的哪一侧。

Meng et al. (2019) 通过对陕北盐盆相邻探井榆 9 井马家沟组的碳同位素演化曲线的研究,认为其恰好对应于全球碳同位素曲线中奥陶纪第二次生物大辐射时期 (即达瑞威尔中晚期)。本次研究运用锶同位素地层学原理对马五段锶同位素年代进行标定,其中大部分样品年龄标定范围介于 461.7 ~ 466.5 Ma, 处于中奥陶世达瑞威尔中期。此外,还通过牙形石生物地层对马家沟组地质年代进行限定。根据岩芯资料识别出的 3 个牙形石带,其地质年代为中奥陶世达瑞威尔中期至晚期。综上三个方面,可以认为镇钾 1 井奥陶系马家沟组地层沉积的地质年代为中奥陶统达瑞威尔中晚期。

3.5.2 三道坎组—桌子山组

Bao Zhidong et al. (1999) 认为三道坎组和桌子山组均属于中奥陶统,且三道坎组相当于马一段,桌子山组相当于马二段—三段。Fei Anwei et al. (2004) 根据岩性和韵律将三道坎组划分为 5 段并识别了该组混合沉积的生物扰动构造,提出三道坎组整体属于下奥陶统。Xi Shengli et al. (2004) 和 Xue Shiyu et al. (2017) 把三道坎组—桌子山组划分至下奥陶统,与下伏上寒武统凤山组呈不整合接触。Guo Yanru et al. (2012)、Zhao Zhenyu et al. (2015)、Wu Dongxu et al. (2018) 认为三道坎组属于下奥陶统而桌子山组划分至中奥陶统。Wang Zhentao et al. (2016) 和 Wu Sujuan et al. (2017) 认

为三道坎组—桌子山组属于中奥陶世大坪期—达瑞威尔阶早期。

Jing et al. (2016)将三道坎组—桌子山组地层共划分出 3 个牙形石生物化石带,其地质年代均属于中奥陶世达瑞威尔中期。通过锶同位素地层学原理进行年代标定的结果显示:其中有 1 个样品归属于中奥陶世,3 个样品归属于早奥陶世。4 个有效样品的锶同位素值普遍高于马五段,表明三道坎组—桌子山组的地质年代早于马家沟组。综上可以认为三道坎组—桌子山组的地质年代为中奥陶世达瑞威尔早中期。

3.6 锶同位素曲线对比

国际上,奥陶纪锶同位素研究获得了一系列喜人的成果。Qing et al. (1998)通过对腕足类化石、牙形石化石及泥晶灰岩的分析,获得了奥陶纪—志留纪锶同位素的长期演化曲线。Denison et al. (1997)以未蚀变的泥晶灰岩为研究对象,总结了北美板块寒武纪—奥陶纪海水锶同位素的变化规律。在此基础上,McArthur et al. (2001)采用 LOWESS 拟合方法反演了奥陶纪海相锶同位素的演化曲线。

在国内,Shields et al. (2003)对扬子板块奥陶纪 29 个腕足类化石进行了锶同位素分析。Jiang Maosheng et al. (2002)以塔里木板块的塔中 12 井为研究对象,对受成岩作用影响较低的泥晶灰岩样品进行了锶同位素测试。Ma Qingyou et al. (2018)对塔中北坡顺南 5 井蓬莱坝组—鹰山组进行了锶同位素研究,由于蓬莱坝组测试样品以灰质云岩和云质灰岩为主,鹰山组沉积期处于开阔水体的环境且

选取的样品多为未发生成岩蚀变的泥晶灰岩,所以该鹰山组的数据更适合用于对比。本次研究以全球奥陶纪锶同位素演化曲线为基准,丰富了鄂尔多斯盆地中东部和西缘锶同位素,通过与塔里木板块和扬子板块同时期锶同位素曲线的对比,总结中国三大板块奥陶纪锶同位素的演化规律。

Shield et al. (2003)公布的扬子板块锶同位素数据覆盖了整个奥陶纪,显示出在早奥陶世锶同位素处于 0.708930 至 0.709120 的高值且变化幅度较小,从中奥陶世达瑞威尔期其值迅速减小,直到晚奥陶世早期降至 0.707867,随后保持相对稳定且小幅增加。扬子板块锶同位素数据与 Qing et al. (1998)和 Denison et al. (1997)公布的数据表现出相同的演化趋势(图 7)。但与其他两者不同的是,Denison et al. (1997)的数据显示出锶同位素值变化速率是相对稳定的,并没有出现在达瑞威尔期陡然下降的现象。

根据 Jing et al. (2016)对鄂尔多斯奥陶系牙形石生物化石带的划分,三道坎组—桌子山组的地质年代归属于达瑞威尔中期,鄂尔多斯盆地西缘锶同位素演化曲线表现为小幅度的震荡且整体为递减的特征,这与 McArthur et al. (2001)公布的拟合曲线在同期表现出一致性。

本次研究的镇钾 1 井马五段与顺南 5 井、塔中 12 井等时地层的锶同位素数据均属于达瑞威尔中晚期。其中,顺南 5 井和塔中 12 井的锶同位素演化曲线皆表现出单调下降的趋势,而塔中 12 井的降幅更大。而镇钾 1 井马五段锶同位素显示出较大幅度的震荡且震荡周期与蒸发岩韵律吻合,从底至顶其

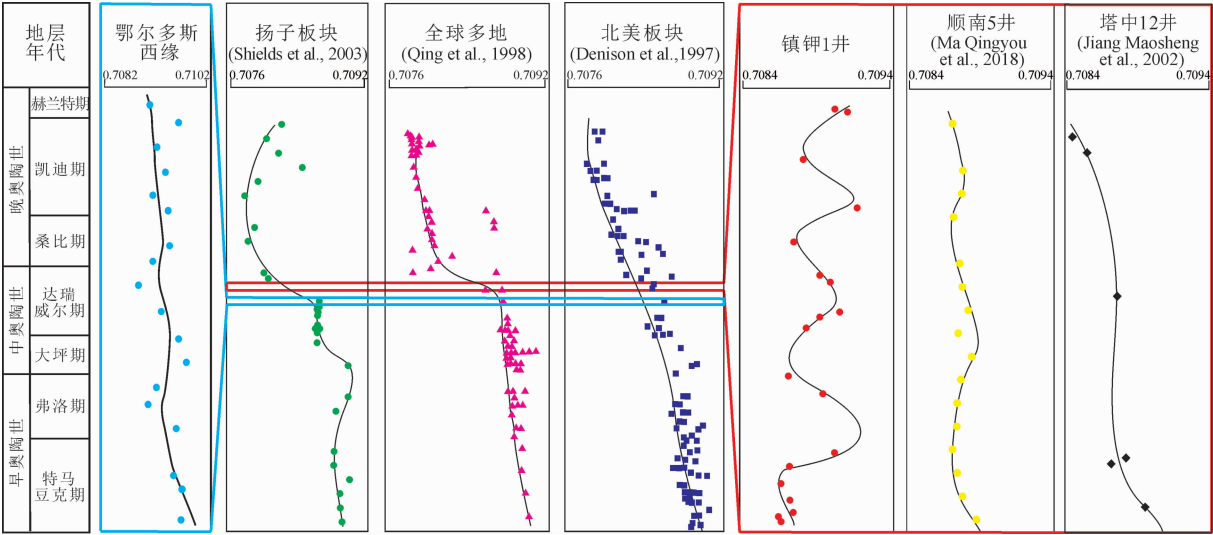


图 7 全球奥陶纪锶同位素演化曲线对比图

Fig. 7 Comparison of global Ordovician Sr isotope evolution curves

值略微增加。这是由于顺南 5 井与塔中 12 井在该沉积期处于开阔台地的环境中,沉积的碳酸盐岩能够反映出当时广海海水锶同位素的特征。而镇钾 1 井马五段沉积期处于局限台地-蒸发台地的环境中,与广海的连通性较差,其锶同位素往往受到陆源物质,蒸发强度等主控因素的制约,无法与全球奥陶纪锶同位素曲线进行对比,但是其变化规律与蒸发岩韵律相匹配,可以作为研究蒸发环境的重要指标。

整体上来看,中国三大板块中以扬子板块奥陶纪锶同位素数据最为完整和连续,而塔里木板块和华北板块仅报道了中奥陶世的部分,除了本次研究的镇钾 1 井马五段,其余均与全球锶同位素演化特征一致。这同时也说明了在局限台地-蒸发台地背景下锶同位素对古环境变化更为敏感,能够作为区域古环境分析的重要依据,但是用于全球性对比显然是不合适的。

4 结论

(1)镇钾 1 井马五段锶同位素自下而上反复震荡,震荡周期与蒸发岩韵律十分吻合,即淡化段锶同位素为低值,蒸发段锶同位素为高值,陆源物质的混入是主控因素。桌子山地区三道坎组—桌子山组锶同位素虽然以小幅波动为特征,但整体上呈现出单调递减趋势,表明海平面整体上是不断上升的。

(2)根据锶同位素地层学原理,以 LOWESS 拟合锶同位素演化曲线为基础,镇钾 1 井马五段通过锶同位素的年龄标定认为其归属于中奥陶世达瑞威尔期,而桌子山地区锶同位素样品由于受到砂岩薄夹层的影响,通过该方法标定地质年代的方法可信度较低。

(3)镇钾 1 井马家沟组可以划分出 3 个牙形石生物化石带,时代为中奥陶世达瑞威尔期中—晚期。桌子山地区三道坎组—桌子山组识别出 3 个牙形石生物化石带,时代归属于中奥陶世达瑞威尔期中期。

(4)根据牙形石生物地层和锶同位素年代标定的结果,结合前人地层划分方案,马家沟组的地质年代为中奥陶统达瑞威尔中—晚期。三道坎组—桌子山组的地质年代早于马家沟组,为中奥陶世达瑞威尔早—中期。

(5)镇钾 1 井马五段锶同位素与全球锶同位素演化特征存在差异,说明了在局限台地-蒸发台地背景下锶同位素对古环境变化更为敏感,能够作为区域古环境分析的重要依据,但不适用于全球性对比。桌子山地区三道坎组—桌子山组由于处于开阔台

地-缓坡的沉积背景下,与全球锶同位素演化曲线拟合度较高。

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References

- Ainsaer L, Kaljo D, Martma T, Meidla T, Männik P, Nõlvak J, Tinn O. 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 294(3~4): 189~201.
- An Taixiang. 1983. Conodonts from North China and Adjacent Areas. Beijing: Science Press, 1~256.
- An Taixiang, Zheng Zhaochang. 1990. Conodonts Surrounding the Ordos Basin. Beijing: Science Press, 1~219.
- Arthur M A, Dean W E, Schlanger S O. 1985. Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes in atmospheric CO₂. *American Geophysical Union*, 32: 504~529.
- Bao Zhidong, Li Rufeng, Feng Zengzhao. 1999. Stratigraphic division and correlation of the Ordovician in the eastern and the western Ordos basin: A review. *Geological Review*, 45(4): 375~381 (in Chinese with English abstract).
- Burke W H, Denison R E, Hetherington E A, Koepnick R B, Nelson H F, Otto J B. 1982. Variation of seawater ⁸⁷Sr/⁸⁶Sr throughout Phanerozoic time. *Geology*, 10(10): 516~519.
- Chen Anqing. 2010. Basin evolution and sediments accumulation during Eopaleozoic in Ordos continental block. Doctoral dissertation of Chengdu University of Technology (in Chinese with English abstract).
- Denison R E, Koepnick R B, Burke W H, Hetherington E A. 1997. Construction of the Cambrian and Ordovician seawater ⁸⁷Sr/⁸⁶Sr curve. *Chemical Geology*, 152(3): 325~340.
- Derry L A, Keto L S, Jacobsen S B, Knoll A H, Swett K. 1989. Sr isotopic variations in upper Proterozoic carbonates from Svalbard and East Greenland. *Geochimica et Cosmochimica Acta*, 53: 2331~2339.
- Edwards C T, Saltzman M R. 2014. Carbon isotope ($\delta^{13}\text{C}$ carb) stratigraphy of the lower-middle Ordovician (Tremadocian-Darriwilian) in the Great basin, western United States: Implications for global correlation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 399: 1~20.
- Ethington R L, Clark D L. 1982. Lower and middle Ordovician conodonts from the Ibex area, western Millard County, Utah. *Brigham Young University Geology Study*, 28: 1~160.
- Fei Anwei, Liu Chenglin, Gan Jun, Zhang Zhongtao. 2004. Bioturbation structures and paleogeography of mixed deposits of the lower Ordovician Sandaokan Formation, Ordos basin. *Geology in China*, 31(4): 347~355 (in Chinese with English abstract).
- Feng Zengzhao. 1998. Lithofacies and Palaeogeography of Ordovician Strata in Ordos. Beijing: Geological Publishing House, 1~152.
- Fu Jinhua, Zheng Congbin. 2001. Evolution between North China sea and Qilian sea of the Ordovician and the characteristics of lithofacies palaeogeography in Ordos basin. *Journal of Palaeogeography*, 3(4): 25~34 (in Chinese with English abstract).
- Guo Yanru, Zhao Zhenyu, Fu Jinhua, Xu Wanglin, Shi Xiaoying, Sun Liuyi, Gao Jianrong, Zhang Yanling, Zhang Yueqiao, Liu Junbang, Liu Hong. 2012. Sequence lithofacies paleogeography of the Ordovician in Ordos basin, China. *Acta Petroli Sinica*, 33(S2): 95~109 (in Chinese with English abstract).
- Guo Yanru, Zhao Zhenyu, Xu Wanglin, Shi Xiaoying, Gao Jianrong, Bao Hongping, Liu Junbang, Zhang Yanling, Zhang

- Yueqiao. 2014. Sequence stratigraphy of the Ordovician system in the Ordos basin. *Acta Sedimentologica Sinica*, 32(1): 44~60 (in Chinese with English abstract).
- He Xunyun, Shou Jianfeng, Shen Anjiang, Wu Xingning, Wang Yongsheng, Hu Yuanyuan, Zhu Yin, Wei Dongxiao. 2014. Geochemical characteristics and origin of dolomite: A case study from the middle assemblage of Majiagou Formation Member 5 of the west of Jingbian gas field. Ordos basin, north China. *Petroleum Exploration and Development*, 41(3): 375~384 (in Chinese with English abstract).
- Howarth R J, Mearthur J M. 1997. Statistics for strontium isotope stratigraphy: A robust lowess fit to the marine Sr - isotope curve for 0 to 206 Ma, with look - up table for derivation of numericage. *Journal of Geology*, 105(4): 441~456.
- Huang Daojun, Wen Caixia, Ji Hailong, Wang Yanqing. 2009. Characteristics and key controlling factors of Ordovician weathering karst crust reservoir in the eastern part of Ordos basin. *Marine Petroleum Geology*, 14(3): 10~18 (in Chinese with English abstract).
- Huang Sijing. 1990. Cathodoluminescence and diagenetic alteration of marine carbonate minerals. *Sedimentary Geology and Tethyan Geology*, 10(4): 9~15.
- Huang Sijing. 1997. Carbon and strontium isotopes of Late Paleozoic marine carbonate rocks in the Upper Yangtze Platform. *Acta Geologica Sinica*, 71(1): 45~53 (in Chinese with English abstract).
- Huang Sijing, Shi He, Zhang Meng, Wu Wenhui, Shen Licheng. 2002. Global correlation of Devonian Sr isotope evolution curves and age assignment of marine strata in Longmenshan. *Progress in Natural Science*, 12(9): 945~951 (in Chinese with English abstract).
- Huang Sijing, Shi He, Mao Xiaodong, Zhang Meng, Shen Licheng, Wu Wenhui. 2003. Diagenetic alteration of earlier Palaeozoic marine carbonate and preservation for the information of sea water. *Journal of Chengdu University of Technology(Science& Technology Edition)*, 30(1): 9~18 (in Chinese with English abstract).
- Huang Sijing, Liu Shugen, Li Guorong, Zhang Meng, Wu Wenhui. 2004a. Strontium isotope composition of marine carbonate and the influence of diagenetic fluid on it in Ordovician. *Journal of Chengdu University of Technology (Science& Technology Edition)*, 31(1): 1~7 (in Chinese with English abstract).
- Huang Sijing, Shi He, Shen Licheng, Zhang Meng and Wu Wenhui. 2004b. Global correlation of Sr isotope curves and marine stratigraphic age assignment of late Cretaceous in Tibet. *Science in China: Earth Sciences*, 34(4): 335~344 (in Chinese with English abstract).
- Huang Sijing, Shi He, Zhang Meng, Wu Wenhui, Shen Licheng. 2004c. Application of strontium isotope stratigraphy to dating Ordovician marine sediments-A case study from the well Tazhong 12 in Tarim basin. *Acta Sedimentologica Sinica*, 22(1): 1~5 (in Chinese with English abstract).
- Huang Sijing, Shi He, Zhang Meng, Wu Wenhui, Shen Licheng, Huang Chenggang. 2005. Strontium isotope age calibration of Rudist Bivalves from late Cretaceous section in southern Tibet. *Earth Science-Journal of China University of Geosciences*, 30(4): 437~442 (in Chinese with English abstract).
- Huang Sijing, Zhang Meng, Sun Zhilei, Hu Zuwei, Wu Sujuan, Pei Changrong. 2006. Age calibration of carbonate samples from the Triassic Feixianguan Formation, well Luoia 2, eastern Sichuan by strontium isotope stratigraphy. *Journal of Chengdu University of Technology (Science& Technology Edition)*, 33(2): 111~116 (in Chinese with English abstract).
- Huang Wenhui, Yang Min, Yu Bingsong, Fan Tailiang, Chu Guangzhen, Wan Huan, Zhu Jingquan, Wu Shiqiang, Wang Xu. 2006. Strontium isotope composition and its characteristics analysis of Cambrian-Ordovician carbonate in Tazhong district, Tarim basin. *Earth Science-Journal of China University of Geosciences*, 31(6): 839~845 (in Chinese with English abstract).
- Ingram B L, Coccioni R, Montanari A, Richter F M. 1994. Strontium isotopic composition of mid-Cretaceous seawater. *Science*, 264(5158): 546~550.
- Jacobsen S B, Kaufman A J. 1999. The Sr, C and O isotopic evolution of Neoproterozoic seawater. *Chemical Geology*, 161(1-3): 37~57.
- Jia Zhenyuan, Li Zhiming, Cai Zhongxian. 1997. Sequence stratigraphy and sea level changes on early Paleozoic paleocontinents and their margins in China. *Earth Science-Journal of China University of Geosciences*, 22(5): 544~551 (in Chinese with English abstract).
- Jiang Maosheng, Zhu Jingquan, Chen Daizhao, Zhang Renhu and Qiao Guangsheng. 2002. Carbon and strontium isotope characteristics of Ordovician carbonate rocks in Tarimbasin and their response to sea level changes. *Science in China*, 32(1): 36~42 (in Chinese with English abstract).
- Jing Xiuchun, Zhou Hongrui, Wang Xunlian. 2015. Ordovician (middle Darriwilian-earliest Sandbian) conodonts from the Wuhai area of Inner Mongolia, North China. *Journal of Paleontology*, 89(05): 768~790 (in Chinese with English abstract).
- Jing Xiuchun, Zhou Hongrui, Wang Xunlian. 2016. Biostratigraphy and biofacies of the middle Darriwilian (Ordovician) conodonts from the Laoshidan section in the western margin of the North China Craton. *Marine Micropaleontology*, 125: 51~65 (in Chinese with English abstract).
- Kaljo D, Martma T, Saadre T. 2007. Post-Hunnebergian Ordovician carbon isotope trend in Baltoscandia, its environmental implications and some similarities with that of Nevada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 245(1~2): 138~155.
- Kaufman A J, Knoll A H, Awramik S M. 1992. Biostratigraphic and chemostratigraphic correlation of Neoproterozoic sedimentary successions: upper Tindir Group, northwestern Canada, as a test case. *Geology*, 20(2): 181~185.
- Koepnick R B, Burke W H, Denison R E, Hetherington E A, Nelson H F, Otto J B, Waite L E. 1985. Construction of the seawater curve for the Cenozoic and retaceous: Supporting data. *Chemical Geology*, 58(1): 55~81.
- Liu Cunge, Li Guorong, Zhang Yiwei, Han Yongqiang, Lu Haitao, Yang Xinyong, Cui Zehong. 2007. Application of strontium isotope to the study of Paleokarst-A case from Ordovician in the Tahe oilfield, Tarim Basin. *Acta Geologica Sinica*, 81(10): 1398~1406 (in Chinese with English abstract).
- Liu Qun, Du Zhiyue, Chen Yuhua. 1997. PotassiumProspecting Prospects of Ordovician in Northern Shaanxi and Carboniferous in Tarim Basin. Beijing: Atomic Energy Press, 1~249.
- Ma Qingyou, Jiang Huashan. 2018. Strontium isotopic curve of the lower Ordovician and the chronostratigraphic division of well Shunnan 5 on northern slope of middle Tarim basin. *Geological Science and Technology Information*, 37(1): 69~73 (in Chinese with English abstract).
- Maloof A C, Schrag D P, Crowley J L, Bowring S A, 2005. An expanded record of Early Cambrian carbon cycling from the Anti-Atlas Margin, Morocco. *Canadian Journal of Earth Sciences*, 42(12): 2195~2216.
- McArthur J M, Howarth R J, Bailey T R. 2001 Strontium isotope stratigraphy: lowess version 3; best fit to the marine Sr - isotope curve for 0~509 Ma and accompanying look - up table for deriving numerical age. *The Journal of Geology*, 109(2): 155~170.
- McArthur J M, Kennedy W J, Chen M, Thirlwall M F, Gale A S. 1994. Strontium isotope stratigraphy for Late Cretaceous time: Direct numerical calibration of the Sr isotope curve based on the US Western Interior. *Palaeogeography Palaeoclimatology Palaeoecology*, 108(1~2): 0~119.
- Meng Fanwei, Zhang Zhili, Yan Xianqin, Ni Pei, Liu Wenhong, Fan Fu, Xie Guwei. 2017. Stromatolites in Middle Ordovician

- carbonate-evaporite sequences and their carbon and sulfur isotopes stratigraphy, Ordos Basin, northwestern China. *Carbonates & Evaporites*, 34(1): 11~20 (in Chinese with English abstract).
- Montañez I P, Banner J L, Osleger D A, Borg L E, Bosserman P J. 1996. Integrated Sr isotope variations and sea-level history of Middle to Upper Cambrian platform carbonates; Implications for the evolution of Cambrian seawater $^{87}\text{Sr}/^{86}\text{Sr}$. *Geology*, 24(10): 917~920.
- Munneke A, Calner M, Harper, David A T, Servais T. 2010. Ordovician and Silurian seawater chemistry, sea level, and climate: a synopsis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 296(3~4): 389~413.
- Munneke A, Zhang Yuandong, Liu Xiao, Cheng Junfeng. 2011. Stable carbon isotope stratigraphy in the Ordovician of South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 307(1~4): 17~43.
- Palmer M R, Edmond J M. 1989. The strontium isotope budget of the modern ocean. *Earth & Planetary Science Letters*, 92(1): 11~26.
- Palmer M R, Elderfield H. 1985. Sr isotope composition of sea water over the past 75 Myr. *Nature*, 314(6011): 526~528.
- Pan Jiahua, Liu Shuqin, Yang Yi, Liu Xueqing. 2002. Sr isotopic compositions and age dating of marine phosphates from Pacific seamounts. *Mineral Deposits*, 21(4): 350~355.
- Popp B N, Podosek F A, Brannon J C, Thomas F A, Jean P. 1986. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in Permo-Carboniferous sea water from the analyses of well-preserved brachiopod shells. *Geochimica et Cosmochimica Acta*, 50(7): 1321~1328.
- Qian Feng, Ai Yongfeng. 2002. Characteristics and evolution of active continental margin during early Palaeozoic era in southern Ordos. *Journal of Earth Sciences and Environment*, 24(1): 18~21 (in Chinese with English abstract).
- Qin Jianhua, Pan Guitang, Du Gu, Ran Jing. 2002. The progress for study on the change of Cenozoic global climate, continental silicate rock weathering and marine strontium isotope. *Acta Petrologica et Mineralogica*, 22(1): 31~35 (in Chinese with English abstract).
- Qing H, Barnes C R, Buhl D, Veizer J. 1998. The strontium isotopic composition of Ordovician and Silurian brachiopods and conodonts: relationships to geological events and implications for coeval seawater. *Geochimica et Cosmochimica Acta*, 62(10): 1721~1733.
- Saltzman M R, Ripperdan R L, Brasier M D, Lohmann K C, Robison R A, Chang W T, Peng S, Ergaliev E K, Runnegar B. 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.
- Serra F, Albanesi G L, Ortega G, Bergström S M. 2015. Biostratigraphy and palaeoecology of Middle-Late Ordovician conodont and graptolite faunas of the Las Chacritas River section, Precordillera of San Juan, Argentina. *Geological Magazine*, 152(5): 813~829.
- Shields G A, Carden G A F, Veizer J, Meidla T, Rong J, Li R. 2003. Sr, C, and O isotope geochemistry of Ordovician brachiopods: A major isotopic event around the Middle-Late Ordovician transition. *Geochimica et Cosmochimica Acta*, 67(11): 2005~2025.
- Stouge S. 2012. Middle Ordovician (late Dapingian-Darriwilian) conodonts from the Cow Head Group and Lower Head Formation, western Newfoundland, Canada. *Canadian Journal of Earth Sciences*, 49(1): 59~90.
- Su Zhongtang. 2011. The study of dolomite genesis and diagenesis system of Majiagou Formation around paleo-uplift, Ordos. Doctoral dissertation of Chengdu University of Technology.
- Tian Jingchun, Zeng Yunfu. 1995. The revolution of the isotopic composition of Strontium in the Permian paleo-ocean in south China. *Acta Sedimentologica Sinica*, 13(4): 125~130 (in Chinese with English abstract).
- Veizer J, D Ala, K Azmy, Bruckschen P, Buhl D. 1999. $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ V-SMOW evolution of Phanerozoic seawater. *Chemical Geology*, 161(1): 1586~1586.
- Wang Lei. 2013. The analysis of dolomite genesis of Zhuozishan Formation, Ordovician the north of Tianhuan, Ordos. Master dissertation of Chengdu University of Technology (in Chinese with English abstract).
- Wang Wenqian, Wang Wei. 2013. Strontium Isotope Stratigraphy. *Journal of Stratigraphy*, 37(4): 566~567 (in Chinese with English abstract).
- Wang Xiaofeng, Chen Xu, Chen Xiaohong, Zhu Ciyang. 1996. Chinese Stratigraphy-Ordovician. Beijing: Geological Publishing House, 1~126.
- Wang Zhentao, Zhou Hongrui, Wang Xunlian, Jing Xiuchun, Zhang Yongsheng, Yuan Lupeng, Shen Zhijun. 2016. The Ordovician basin prototype in the northwest Ordos basin: Constraint from the Ordovician sedimentary respond in the Helan—Zhuozhi Mountains. *Geological Review*, 62(4): 1041~1061 (in Chinese with English abstract).
- Wang Zhihao, Bergstrom S M, Zhen Yongyi, Zhang Yuanzhang, Wu Rongchang. 2014. A revision of the Darriwilian biostratigraphic conodont zonation in Tangshan. Hebei Province, based on new conodont collections. *Acta Palaeontologica Sinica*, 53(1): 1~15 (in Chinese with English abstract).
- Wang Zhihao, Zhen Yongyi, Zhang Yuanzhang, Wu Rongchang. 2016. Review of Ordovician conodont biostratigraphy in the different facies of north China. *Journal of Stratigraphy*, 40(1): 1~16 (in Chinese with English abstract).
- Wu Dongxu, Zhou Jingao, Wu Xingning, Ding Zhenchun, Yuzhou, Wang Shaoyi, Li Weiling, Wang Shumin. 2018. Lithofacies and palaeogeography of the early-middle Ordovician in the western Ordos basin. *Geological Journal of China Universities*, 24(5): 123~136 (in Chinese with English abstract).
- Wu Sujuan, Zhang Yongsheng, Xing Enyuan. 2016. Geochemistry of Ordovician detrital rocks and its constrains on provenance in Zhuozishan area, northwest Ordos basin. *Acta Geologica Sinica*, 90(8): 1860~1873 (in Chinese with English abstract).
- Wu Sujuan, Zhang Yongsheng, Xing Enyuan. 2017. Zircon U-Pb ages and Hf isotope characteristics and their geological significance of Tuff in Wulalike Formation in the northwestern Ordos basin. *Geological Review*, 63(5): 1309~1327 (in Chinese with English abstract).
- Xi Shengli, Zheng Congbin, Li Zhenhong. 2004. Geochemical characteristics and its sedimentary environment significance of the Ordovician in the western margin of Ordos basin. *Journal of Palaeogeography*, 6(2): 196~206 (in Chinese with English abstract).
- Xing Enyuan, Zhang Yongsheng, Zheng Mianping, Wang Zhuozhuo, Pan Wei, Zhai Daxing, Wu Feimeng. 2014. Characteristics and implications significance for carbon and oxygen isotope continuous change of Zhenjial well in the northern Shaanxi salt basin. *Acta Geologica Sinica* (English Edition), 88(A1): 269~271.
- Xue Shiyu, Fu Shiyi, Hou Mingcai, Gao Xing, Su Zhongtang, Hu Shangcai, Ju Lijuan. 2017. Characteristics and implications of carbon and oxygen isotopes in dolomites of the Ordovician Zhuozishan Formation in northern Tianhuan depression, Ordos basin. *Petroleum Geology & Experimental*, 39(6): 842~848 (in Chinese with English abstract).
- Yan Quanren, Wang Zongqi, Yan Jun, Wang Tao, Zhang Hongyuan, Xiang Zhongjin, Jiang Chunfa, Gao Lianda. 2009. Timing of the transformation from seafloor spreading on the south margin of the North China block to subduction within the north Qinling orogenic belt. *Acta Geologica Sinica*, 83(11): 1565~1583 (in Chinese with English abstract).
- Yang Jiedong, Sun Weiguo, Wang Zongzhe, Xue Yaosong, Tao Xiancong. 1999. Variations in Sr and C isotopes and Ce anomalies in successions from China: Evidence for the

- oxygenation of Neoproterozoic seawater? *Precambrian Research*, 93(2~3): 215~233.
- Yang Jiedong, Wang Zongzhe. 1994. C, O and Sr isotopes of early paleozoic strata in the Kalpin area. *Xinjiang. Geological Review*, 40(4): 377~385.
- Yang Junjie. 2002. *Tectonic Evolution and Oil and Gas Distribution in Ordos Basin*. Beijing: Petroleum Industry Press, 1~228.
- Yang Xiyan, Bao Hongping, Ren Junfeng, Ma Zhanrong. 2015. Types of dolomites and characteristics of stable isotope from the Ma55 Sub-member of Ordovician Majiagou Formation in Ordos basin. *Natural Gas Geoscience*, 26(4): 650~656 (in Chinese with English abstract).
- Yuan Weiguo, Zhao Yiming. 1996. Characteristics and evolution of passive continental margin during early Palaeozoic era in southern Ordos. *Journal of Northwest University: Natural Science Edition*, 26(5): 451~454.
- Zhang Jin, Li Jinyi, Liu Jianfeng, Li Yanfeng, Qujunfeng, Feng Qianwen. 2012. The relationship between the Alxa Block and the North China Plate during the early Paleozoic: New information from the Middle Ordovician detrital zircon ages in the eastern Alxa block. *Acta Petrologica Sinica*, 28(9): 2912~2934 (in Chinese with English abstract).
- Zhang Jin, Ma Zongjin and Ren Wenjun. 2004. Re-discussion on natures of extension in Helanshan region before Cenozoic era. *Acta Petrologica Sinica*, 25(6): 8~17 (in Chinese with English abstract).
- Zhang Yongsheng, Xing Enyuan, Chen Wenxi. 2014. Comparative study of palaeo-epicontinental marine basin potash-forming conditions between China and foreign countries with special reference to potash-forming possibilities in North China. *Mineral Deposits*, 33(5): 897~908.
- Zhao Guowei. 2013. Middle-Late Ordovician sea-level changes in the Bachu area, Tarim basin, Xinjiang: Carbon, oxygen and strontium isotope records. Doctoral dissertation of Jilin University (in Chinese with English abstract).
- Zhao Zhenyu, Sun Yuanshi, Li Chengshan, Zhang Qing. 2015. Stratigraphic division and correlation of Ordovician in Ordos Basin. *Special Oil and Gas Reservoirs*, 22(5): 9~17 (in Chinese with English abstract).
- ## 参 考 文 献
- 安太庠. 1983. 华北及邻区牙形石. 北京: 科学出版社, 1~256.
- 安太庠, 郑昭昌. 1990. 鄂尔多斯盆地周缘的牙形石. 北京: 科学出版社, 1~219.
- 鲍志东, 李儒峰, 冯增昭. 1999. 鄂尔多斯盆地东西部奥陶系对比再研究. *地质论评*, 45(4): 375~381.
- 陈安清. 2010. 鄂尔多斯地块早古生代盆地演化与物质聚集规律. 成都理工大学博士学位论文.
- 费安玮, 刘成林, 甘军, 张忠涛. 2004. 鄂尔多斯盆地三道坎组混合沉积的生物扰动构造与古地理. *中国地质*, 31(4): 347~355.
- 冯增昭. 1998. 鄂尔多斯奥陶纪地层岩石岩相古地理. 北京: 地质出版社, 1~152.
- 付金华, 郑聪斌. 2001. 鄂尔多斯盆地奥陶纪华北和祁连海演变及岩相古地理特征. *古地质量报*, 3(4): 25~34.
- 郭彦如, 赵振宇, 付金华, 徐旺林, 史晓颖, 孙六一, 高建荣, 张延玲, 张月巧, 刘俊榜, 刘虹. 2012. 鄂尔多斯盆地奥陶纪层序岩相古地理. *石油学报*, 33(S2): 95~109.
- 郭彦如, 赵振宇, 徐旺林, 史晓颖, 高建荣, 包洪平, 刘俊榜, 张延玲, 张月巧. 2014. 鄂尔多斯盆地奥陶系层序地层格架. *沉积学报*, 32(1): 44~60.
- 贺训云, 寿建峰, 沈安江, 吴兴宁, 王永生, 胡圆圆, 朱吟, 韦东晓. 2014. 白云岩地球化学特征及成因——以鄂尔多斯盆地靖西马五段中组合为例. *石油勘探与开发*, 41(3): 375~384.
- 黄道军, 文彩霞, 季海银, 王彦卿. 2009. 鄂尔多斯盆地东部奥陶系风化壳储层特征及主控因素分析. *海相油气地质*, 14(3): 10~18.
- 黄思静. 1990. 海相碳酸盐矿物的阴极发光性与其成岩蚀变的关系. *沉积与特提斯地质*, 10(4): 9~15.
- 黄思静. 1997. 上扬子地台区晚古生代海相碳酸盐岩的碳、锶同位素研究. *地质学报*, 71(1): 45~53.
- 黄思静, 石和, 张萌, 武文慧, 沈立成. 2002. 门山泥盆纪锶同位素演化曲线的全球对比及海相地层的定年. *自然科学进展*, 12(9): 945~951.
- 黄思静, 石和, 毛晓冬, 张萌, 沈立成, 武文慧. 2003. 早古生代海相碳酸盐的成岩蚀变性及其对海水信息的保存性. *成都理工大学学报(自然科学版)*, 30(1): 9~18.
- 黄思静, 刘树根, 李国蓉, 张萌, 武文慧. 2004a. 奥陶系海相碳酸盐锶同位素组成及受成岩流体的影响. *成都理工大学学报(自然科学版)*, 31(1): 1~7.
- 黄思静, 石和, 沈立成, 张萌, 武文慧. 2004b. 西藏晚白垩世锶同位素曲线的全球对比及海相地层的定年. *中国科学: 地球科学*, 34(4): 335~344.
- 黄思静, 石和, 张萌, 武文慧, 沈立成. 2004c. 锶同位素地层学在奥陶系海相地层定年中的应用——以塔里木盆地塔中12井为例. *沉积学报*, 22(1): 1~5.
- 黄思静, 石和, 张萌, 武文慧, 沈立成, 黄成刚. 2005. 西藏南部晚白垩世厚壳蛤的锶同位素年龄标定. *地球科学*, 30(4): 437~442.
- 黄思静, 张萌, 孙治雷, 胡作维, 吴素娟, 裴昌蓉. 2006. 川东L2井三叠系飞仙关组碳酸盐样品的锶同位素年龄标定. *成都理工大学学报(自然科学版)*, 33(2): 111~116.
- 黄文辉, 杨敏, 于炳松, 樊太亮, 初广震, 万欢, 朱井泉, 吴仕强, 王旭. 2006. 塔中地区寒武系—奥陶系碳酸盐岩 Sr 元素和 Sr 同位素特征. *地球科学*, 31(6): 839~845.
- 贾振远, 李志明, 蔡忠贤. 1997. 中国古大陆及其边缘早古生代层序地层及海平面变化的基本特征. *地球科学*, 22(5): 544~551.
- 江茂生, 朱井泉, 陈代钊, 张任祐, 乔广生. 2002. 塔里木盆地奥陶纪碳酸盐岩碳、锶同位素特征及其对海平面变化的响应. *中国科学*, 32(1): 36~42.
- 刘存革, 李国蓉, 张一伟, 韩拥强, 吕海涛, 杨新勇, 崔泽宏. 2007. 锶同位素在古岩溶研究中的应用——以塔河油田奥陶系为例. *地质学报*, 81(10): 1398~1406.
- 刘群, 杜之岳, 陈郁华. 1997. 陕北奥陶系和塔里木石炭系钾盐找矿远景. 北京: 原子能出版社, 1~249.
- 马庆佑, 蒋华山. 2018. 塔中北坡顺南5井下奥陶统锶同位素曲线及地层划分. *地质科技情报*, 37(1): 69~73.
- 潘家华, 刘淑琴, 杨忆, 刘学清. 2002. 太平洋海山磷酸盐的锶同位素成分及形成年代. *矿床地质*, 21(4): 350~355.
- 钱锋, 艾永峰. 2002. 鄂尔多斯南部地区早古生代主动大陆边缘演化特征. *地球科学与环境学报*, 24(1): 18~21.
- 秦建华, 潘桂荣, 杜谷, 冉敬. 2002. 新生代气候变化与陆地硅酸盐岩风化和海洋 Sr 同位素研究. *矿物岩石*, 22(1): 31~35.
- 苏中堂. 2011. 鄂尔多斯盆地古隆起周缘马家沟组白云岩成因及成岩系统研究. 成都理工大学博士学位论文.
- 田景春, 曾允孚. 1995. 中国南方二叠纪古海洋锶同位素演化. *沉积学报*, 13(4): 125~130.
- 汪啸风, 陈旭, 陈孝红, 朱慈英. 1996. 中国地层典—奥陶系. 北京: 地质出版社, 1~126.
- 王磊. 2013. 鄂尔多斯盆地天环北段奥陶系桌子山组白云岩成因分析. 成都理工大学硕士学位论文.
- 王文倩, 王伟. 2013. 锶同位素地层学. *地层学杂志*, 37(4): 566~567.
- 王振涛, 周洪瑞, 王训练, 景秀春, 张永生, 袁路朋, 沈智军. 2016. 鄂尔多斯盆地西缘北部奥陶纪盆地原型: 来自贺兰山和桌子山地区奥陶系的沉积响应. *地质论评*, 62(4): 1041~1061.
- 王志浩, Bergstrom S M, 甄勇毅, 张元动, 吴荣昌. 2014. 河北唐山达瑞威尔阶(Darriwilian)牙形刺生物地层的新认识. *古生物学报*, 53(1): 1~15.
- 王志浩, 甄勇毅, 张元动, 吴荣昌. 2016. 中国华北不同相区奥陶纪牙形刺生物地层再认识. *地层学杂志*, 40(1): 1~16.
- 吴东旭, 周进高, 吴兴宁, 丁振纯, 于洲, 王少依, 李维岭, 王淑敏. 2018. 鄂尔多斯盆地西缘早中奥陶世岩相古地理研究. *高校地质学报*, 24(5): 123~136.
- 吴素娟, 张永生, 邢恩袁. 2017. 鄂尔多斯盆地西北缘奥陶纪凝灰岩锆石 U-Pb 年龄、Hf 同位素特征及地质意义. *地质论评*, 63(5):

1309~1327.

- 吴素娟,张永生,邢恩袁. 2016. 桌子山地区奥陶系乌拉拉克组碎屑岩地球化学特征及其对物源的制约. 地质学报, 90(8): 1860~1873.
- 席胜利,郑聪斌,李振宏. 2004. 鄂尔多斯盆地西缘奥陶系地球化学特征及其沉积环境意义. 古地理论, 6(2): 196~206.
- 薛时雨,付斯一,侯明才,高星,苏中堂,呼尚才,朱莉娟. 2017. 鄂尔多斯盆地天环坳陷北段桌子山组白云岩碳氧同位素特征及意义. 石油实验地质, 39(6): 842~848.
- 闫全人,王宗起,闫臻,王涛,张宏远,向忠金,姜春发,高联达. 2009. 从华北陆块南缘大洋扩张到北秦岭造山带板块俯冲的转换时限. 地质学报, 83(11): 1565~1583.
- 杨杰东,王宗哲. 1994. 新疆新型柯坪地区早古生代地层的碳、氧和锶同位素. 地质论评, 40(4): 377~385.
- 杨俊杰. 2002. 鄂尔多斯盆地构造演化与油气分布规律. 北京: 石油工业出版社, 1~228.

- 杨西燕,包洪平,任军峰,马占荣. 2015. 鄂尔多斯盆地马家沟组马五₂亚段白云岩类型及稳定同位素特征. 天然气地球科学, 26(4): 650~656.
- 袁卫国,赵一鸣. 1996. 鄂尔多斯南部地区早古生代被动大陆边缘特征与演化. 西北大学学报: 自然科学版, 26(5): 451~454.
- 张进,李锦秩,刘建峰,李岩峰,曲军峰,冯乾文. 2012. 早古生代阿拉善地块与华北地块之间的关系: 来自阿拉善东缘中奥陶统碎屑锆石的信息. 岩石学报, 28(9): 2912~2934.
- 张进,马宗晋,任文军. 2004. 再论贺兰山地区新生代之前拉张活动的性质. 石油学报, 25(6): 8~17.
- 张永生,邢恩袁,陈文西. 2014. 国内外古陆表海盆成钾条件对比—兼论华北成钾的可能性. 矿床地质, 33(5): 897~908.
- 赵国伟. 2013. 新疆巴楚地区中一晚奥陶世海平面变化: 碳、氧、锶同位素记录. 吉林大学博士学位论文.
- 赵振宇,孙远实,李程善,张庆. 2015. 鄂尔多斯盆地奥陶系地层划分与对比研究. 特种油气藏, 22(5): 9~17.

Geochemical characteristics of Ordovician strontium isotope in the Ordos basin

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Abstract

The research on Sr isotope of carbonate rocks in the Ordos basin mainly focuses on the identification and classification of diagenesis. In this study, the fifth Member of the Majiagou Formation (hereinafter referred to as Ma5) in the well Zhenjia-1 and Sandaokan Formation-Zhuozishan Formation in the western margin of the Ordos basin was selected as the research object. This study firstly reports Sr isotopic data of carbonate rocks which are not influenced by diagenesis. Based on the principle of Sr isotope stratigraphy, the characteristics of sedimentary environment were restored and the Ordovician stratigraphic framework was addressed. The following understanding has been obtained. (1) Ma5 Sr isotope of the well Zhenjia-1 is characterized by repeated vibration, but slightly increasing from bottom to top, with oscillation period coincidentally with evaporative rhythm. While Sr isotopes of the Sandaokan and Zhuozishan formations are characterized by moderate fluctuation and decrease generally. (2) Geological age of the Majiagou Formation can be assigned to the middle-late Darriwillian while the counterpart in the Sandaokan and Zhuozishan formations is earlier and is assigned to the early-middle Darriwillian. (3) Ma5 was deposited under the background of restricted platform-evaporation platform and its Sr curve differs from the global curve in Ordovician, suggesting that Sr isotope is more sensitive to the variation of paleoenvironment and could become an important indicator for regional paleoenvironmental comparison. The Sandaokan and Zhuozishan formations in the Zhuozishan area deposited under the background of open platform-carbonate slope and its Sr curve corresponds well with global curve. This study provides not only new fundamental data for global Sr isotope curve but also new evidence for comparison of the sedimentary and tectonic differences of strata in the Ordos basin.

Key words: Ordos basin; Ordovician; strontium isotope stratigraphy; conodont zones