

柴西上干柴沟组中上段介壳微量元素古环境古气候意义

陈伟^{1,2}, 李璇^{1,2}, 曾亮^{1,2}, 王庆同^{1,2,3}, 焦学尧^{1,2}, 杨平⁴, 江小青⁴, 马锦龙^{1,2}

1. 兰州大学地质科学与矿产资源学院, 兰州 730000
2. 甘肃省西部矿产重点实验室, 兰州 730000
3. 武警黄金第七支队, 山东烟台 264004
4. 中国石油青海油田分公司勘探开发研究院, 甘肃敦煌 736202

摘要 介壳微量元素具有重要的沉积古环境古气候意义, 结合介壳微量元素含量变化特征和介壳化石组合生态环境特征可得到柴达木盆地西部上干柴沟组中上段更为详尽的古环境古气候演化特征。柴达木盆地西部上干柴沟组中上段介壳微量元素比值 Sr/Ca、Ba/Ca、U/Ca 及元素 Sr、Ba、U 在 A 阶段(28.35~26.42 Ma) 值较低, B 阶段(26.42~23.08 Ma) 值整体较高, 段末值有所下降, C 阶段(23.08~22.33 Ma) 值明显上升, Mn/Ca 和 Mn 值变化大致相反。A 阶段 Sr/Ca 和 Sr 均值(分别为 0.002 278、 37.76×10^{-9}) 较低, B 阶段均值(分别为 0.003 347、 41.46×10^{-9}) 较高, C 阶段二者均值(分别为 0.003 346、 56.06×10^{-9}) 也较高, Ba/Ca、U/Ca、B、U 有着类似的平均值变化特征, Mn/Ca 和 Mn 值有着相反的平均值变化特征。同时相应各阶段介壳化石组合有所不同。通过介壳微量元素变化及化石组合特征, 结合同期深海氧同位素及前人研究成果表明, 上干柴沟组中上段柴西古湖古环境古气候演化特征为: A 阶段, 盐度较低和还原性较强, 水位较高, 气候相对温暖润湿; B 阶段, 整体盐度较高和氧化性较强, 水位较浅, 气候整体炎热干旱, 段末气候干旱程度降低; C 阶段, 盐度和氧化性增高, 湖水变浅, 气候向冷干演化, 响应了早中新世中国西北内陆干旱化。该地区该时段古气候主要受全球气候演化和青藏高原隆升的影响, 与副特提斯海西退也有一定关系。

关键词 柴达木盆地; 上干柴沟组; 介壳类; 微量元素; 古环境

第一作者简介 陈伟, 男, 1989 年出生, 硕士研究生, 地层古环境演化, E-mail: chenw16@lzu.edu.cn

通信作者 马锦龙, 男, 副教授, E-mail: mjinlong@lzu.edu.cn

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0 引言

介形虫是自寒武纪以来生活在海洋、湖泊、河流等水体当中属节肢动物门甲壳纲介形亚纲的微体动物^[1], 不仅其生态特征和种属组合可以进行古环境的研究^[2], 而且利用介壳微量元素地球化学进行古环境的研究越来越多^[3-6]。与湖泊自生碳酸盐相比, 介壳地球化学在研究古环境古气候方面有着明显的优势, 介形虫在脱壳后长新壳的过程中, 直接从其生活的水体中摄取化学元素而建造新壳^[7]。新壳是在很短的时间内分泌形成的, 其受成岩作用影响较小, 避免了外源碳酸岩碎屑的干扰, 较好地记录了当时水体的环境信息^[8-12]。

柴达木盆地是青藏高原北缘最大的高原内部盆地, 沉积了巨厚的新生代沉积物^[13-15]。根据前人研究^[16-20], 柴达木盆地新生界自下而上划分为路乐河组、下干柴沟组、上干柴沟组、下油砂山组、上油砂山组、狮子沟组及七个泉组共七个地层组。上干柴沟组沉积期柴达木盆地西部为湖盆扩大和稳定沉降阶段^[21], 前人^[16-17, 22-25]通过古生物化石、孢粉、全岩地球化学等研究表明柴西上干柴沟组沉积期主要以亚热带干旱气候为主, 但上干柴沟组中上段更为详尽的古环境古气候演化研究缺乏, 而通过介壳地球化学与介壳化石生态学结合来重建该阶段古环境古气候的研究更为缺乏。本文通过对柴达木盆地西部上干柴沟组中上段介壳微量元素与化石生态特征进行分

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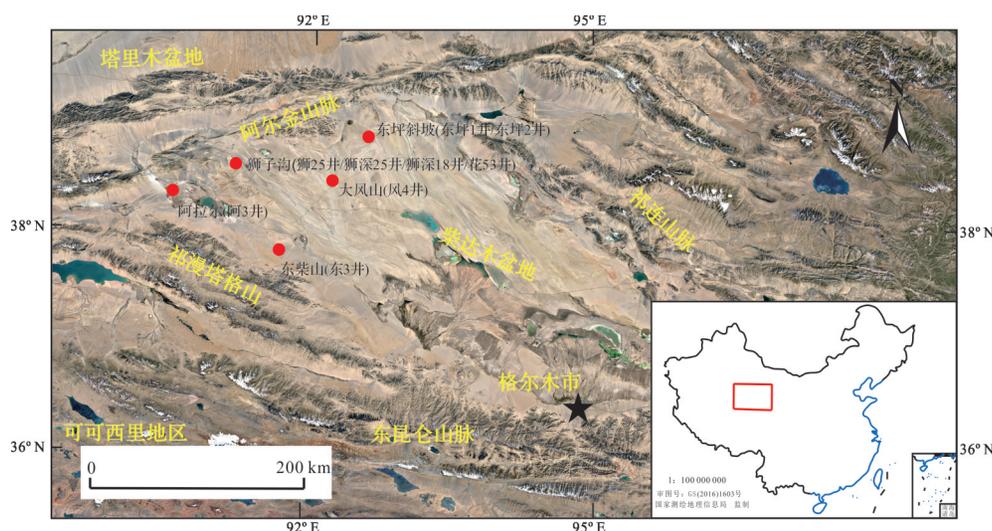


图1 柴达木盆地西部位置及取样地点图

Fig.1 Sampling location in the western Qaidam Basin

析,探讨了该区域(28.35~22.33 Ma)的古环境古气候演化,对深入认识该阶段的古环境古气候演化具有一定意义。

1 研究区地质概况

柴达木盆地是青藏高原东北缘的巨大山间盆地^[14,26-27],位于90°~99° E,35°~39° N之间,为西宽东窄的菱形盆地,呈北西西—南东方向延伸(图1)。柴达木盆地主要被三大山脉所围限,西北为阿尔金山脉,东北为祁连山脉,南部为东昆仑山脉。柴达木盆地大地构造处于亚洲中轴域和特提斯—喜马拉雅构造域的结合部位^[28],盆地新生代构造演化主要受印度板块不断向亚欧板块碰撞导致青藏高原隆升远程效应和特提斯海的阶段性俯冲消减及退却闭合作用的影响^[29-30]。

2 采样与方法

所有介壳样品都取自钻井岩芯,化石的采集、挑选及鉴定是在青海油田勘探开发研究院完成。由于很难在同一口钻井中取到连续的介壳化石,样品取自柴达木盆地西部的东坪斜坡构造(东坪1井/东坪2井)、狮子沟构造(狮25井/狮深25井/狮深18井/花53井)、东柴山构造(东3井)、阿拉尔构造(阿3井)、大风山构造(风4井)的9口石油钻井(图1),共计16个样品。采样岩性主要以泥岩和砂质泥岩为主,还有少量粉砂岩、泥灰岩及页岩,介壳样品包括9个

Eucypris, 5个*Hemicyprinotus*, 2个*Youshashania*。部分介壳样品扫描电镜照片如图2。

前人对柴达木盆地新生代地层做了较多的古地磁年龄研究^[18,31-34]。本文首先通过介壳化石地层分布,结合柴达木盆地西部上干柴沟组年代归属研究^[20,35]和最新国际地层年表^[36],确定了介壳样品年代归属,然后依据王亚东等^[33-34]确定的该组古地磁年龄(31.5~22 Ma),根据取样井顶底深度、平均沉积速率及采样深度确定了每个介壳样品的地层年龄,并拼接成了综合年龄柱(图3),计算的介壳样品地层年龄范围与介壳化石确定的基本年代一致,之后结合岩性、介壳化石地层分布及平均沉积速率绘制了综合地层图(图4)。样品地层年龄计算公式如下:

$$SR=(B-A)/(Z-Y)$$

式中, SR (m/Ma)为平均沉积速率, A (m)、 B (m)分别为沉积组的顶和底($A<B$), Y (Ma)、 Z (Ma)分别为沉积组 A 和 B 的顶底年龄($Y<Z$)。

$$T_x=Z-(B-X)/SR$$

式中, T_x (Ma)为采样深度为 X (m)($A\leq X\leq B$)样品的地质年龄,最终计算得出上干柴沟组16个介壳样品的地层年龄如表1。

本次介壳样品微量元素前处理和测试均在中国科学院青藏高原研究所元素地球化学实验室完成,测试仪器为美国Thermo公司X Series电感耦合等离子体光谱仪(ICP-MS),平行测试空白样和标准样品,保证精度为:1 $\mu\text{g/L-Sr}$, 15 $\mu\text{g/L-Ca}$, Sr/Ca值精度小于0.1 mol/mol,介壳微量元素测试结果及由此计算的比值如表1。

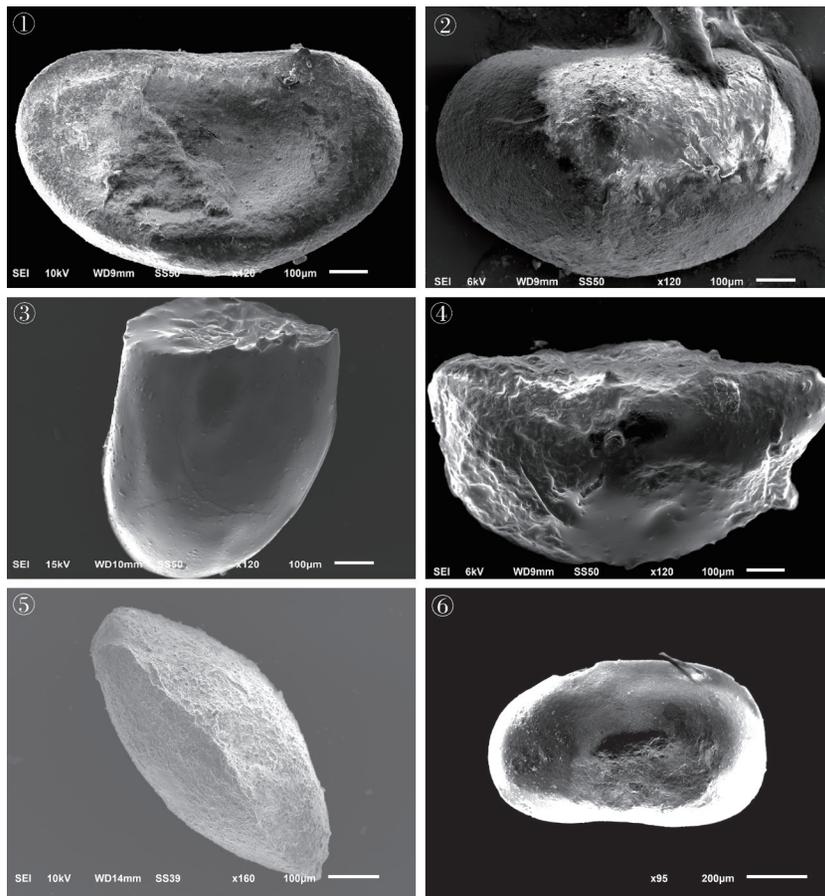


图2 柴西上干柴沟组中上段部分介壳化石扫描电镜照片

① *Youshashania*, 正面, 东坪1井 (250 m); ② *Youshashani*, 背面, 东坪1井 (250 m); ③ *Hemicyprinus*, 正面, 花53井 (1 480 m);
④ *Hemicyprinus*, 背面, 花53井 (1 480 m); ⑤ *Eucypris*, 侧面, 阿3井 (1 510 m); ⑥ *Hemicyprinus*, 正面, 狮25井 (1 560 m)

Fig.2 SEM images of ostracod shell fossils from the middle and upper section of Upper Ganchaigou Formation, western Qaidam Basin

3 柴西上干柴沟组中上段介壳微量元素变化特征

本次所测试的16个介壳样品中,年龄为23.208 6 Ma和24.853 4 Ma的两个样品Sr、Ba含量出现了明显异常(表1),其Sr含量分别为 $2\ 462 \times 10^{-9}$ 和 $9\ 342 \times 10^{-9}$,Ba含量分别为 $1\ 829 \times 10^{-9}$ 和 $4\ 676 \times 10^{-9}$,而其他14个样品的Sr含量介于 $4.16 \times 10^{-9} \sim 87.44 \times 10^{-9}$,Ba含量介于 $1.39 \times 10^{-9} \sim 93.32 \times 10^{-9}$ 。上述两个样品Sr、Ba含量异常的可能原因是极端沉积环境或特殊埋葬条件造成的,比如Mg含量极高的水体会造成介壳Sr含量的异常。为确保数据的可靠性,后文分析和讨论仅涉及其余14个样品数据。

由图5、图6可知,柴达木盆地西部上干柴沟组中上段介壳微量元素比值Sr/Ca、Ba/Ca、U/Ca、Mn/Ca和介壳元素Ca、Sr、Ba、U、Mn具有明显的三阶段变化

特征:A阶段(28.35~26.42 Ma)、B阶段(26.42~23.08 Ma)及C阶段(23.08~22.33 Ma)。

3.1 介壳微量元素比值变化特征

整体上介壳Sr/Ca、Ba/Ca、U/Ca在上述三个阶段变化趋势相似,Mn/Ca变化趋势相反(图5),它们各阶段平均值不同(表2)。A阶段,Sr/Ca、Ba/Ca整体上也为低值,平均值分别为0.002 278、0.000 539,U/Ca整体上也为低值且有轻微下降趋势,平均值为0.000 012,Mn/Ca有明显的上升趋势且平均值(0.012 866)为三个阶段最高;B阶段,Sr/Ca平均值为三个阶段最高(0.003 347),Ba/Ca的平均值(0.000 796)高于A阶段,U/Ca平均值(0.000 022)也为三个阶段最高,Mn/Ca平均值(0.005 153)最低;C阶段,Sr/Ca和Ba/Ca呈明显上升趋势,平均值分别为0.003 346、0.002 059,U/Ca也呈现上升趋势,平均值为0.000 005,而Mn/Ca呈明显下降趋势,平均值为0.009 809。

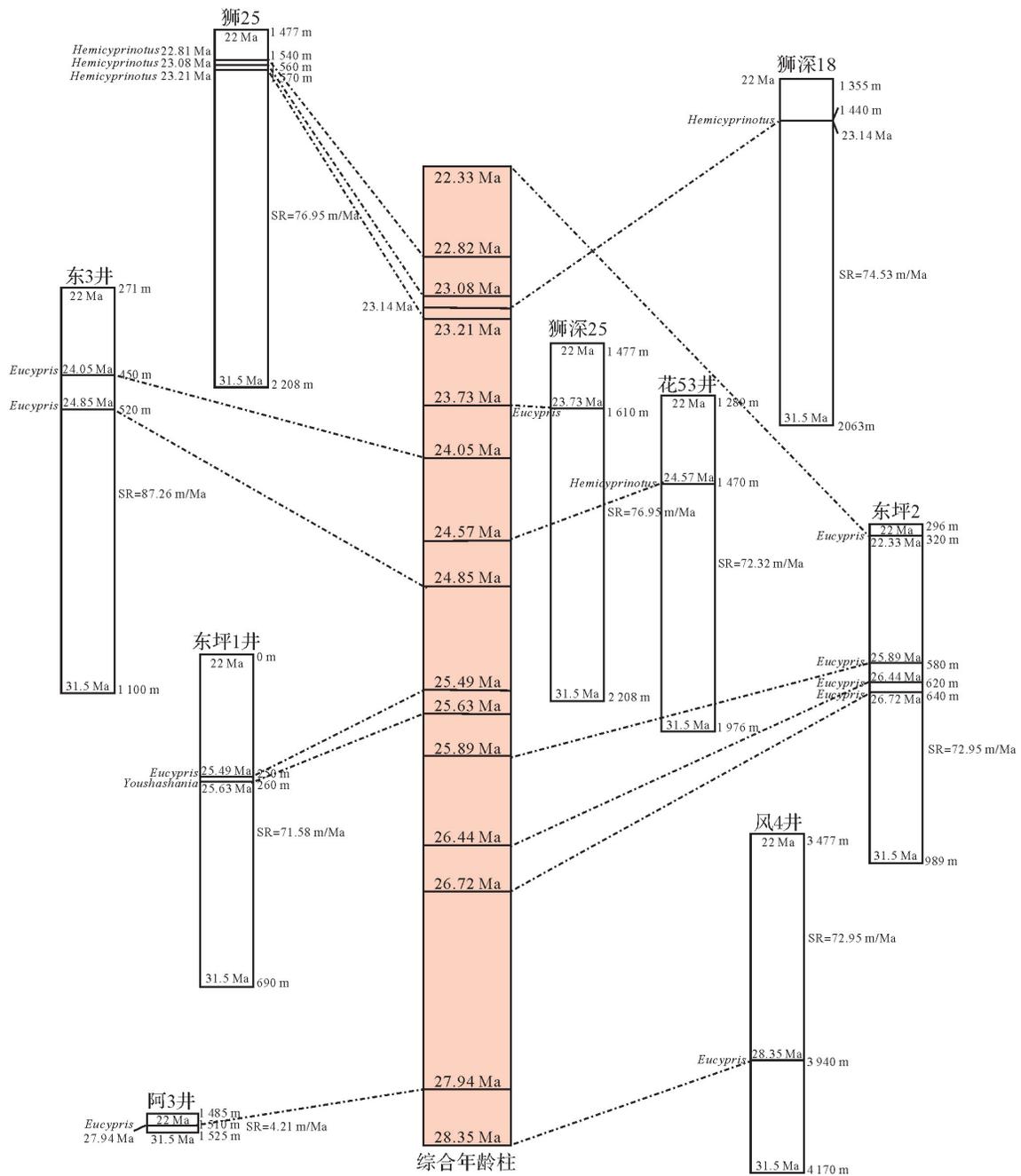


图3 柴西上干柴沟组中上段取样井综合年龄柱拼接图
 SR为取样井地层平均沉积速率;古地磁年龄根据王亚东等^[33-34]

Fig.3 Comprehensive age column splicing map of sampling drilling, upper and middle section of Upper Ganchaigou Formation, western Qaidam Basin

SR is the average sedimentary rate; paleomagnetic ages after Wang *et al.* ^[33-34]

3.2 介壳微量元素变化特征

与微量元素比值类似,介壳Ca、Sr、Ba、U总体上变化趋势相似,Mn呈现相反变化趋势(图6),它们各阶段平均值也不同(表2)。Ca在A、B、C三个阶段的平均值变化不同于Sr、Ba、U,平均值A阶段(14 885×10⁻⁹)高于B阶段(12 969×10⁻⁹),C阶段(16 330×10⁻⁹)最高。A阶段,Sr、Ba从原有水平下降至最低且平均值(分别为

37.76×10⁻⁹、8.21×10⁻⁹)为三个阶段最低,U呈下降趋势,平均值为0.21×10⁻⁹,Mn整体为高值且平均值(173.53×10⁻⁹)最高;B阶段,Sr、Ba、U平均值都高于A阶段,值分别为41.46×10⁻⁹、9.58×10⁻⁹、0.27×10⁻⁹,Mn平均值(58.78×10⁻⁹)最低;C阶段,Sr、Ba呈上升趋势,平均值分别为56.06×10⁻⁹、38.27×10⁻⁹,U也呈上升趋势而Mn呈明显下降趋势,平均值分别为0.10×10⁻⁹、153.10×10⁻⁹。

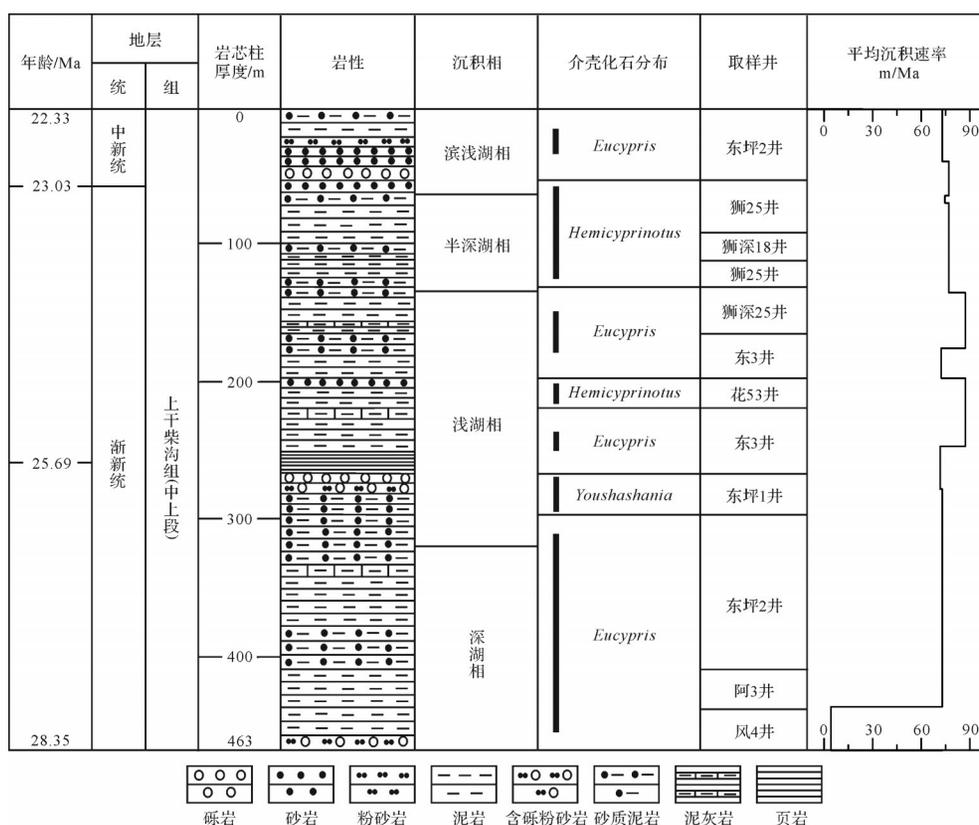


图4 柴西上干柴沟组中上段综合地层图

岩性和沉积相根据取样井及柴西西岔沟标准剖面据张伟林^[19]和 Xu et al.^[37]; 古地磁年龄据王亚东等^[33-34]

Fig.4 Comprehensive stratigraphic map for upper and middle sections of Upper Ganchaigou Formation, western Qaidam Basin lithology based on sampling drilling and the standard profile of Xichagou (Zhang^[19], Xu et al.^[37]); paleomagnetic ages after Wang et al.^[33-34]

表1 上干柴沟组中上段介壳微量元素与比值及年龄

Table 1 Trace elements and ratios with ages of ostracod shells in the upper-middle section of Upper Ganchaigou Formation

样品年龄/Ma	Ca/ $\times 10^{-9}$	Sr/ $\times 10^{-9}$	Ba/ $\times 10^{-9}$	U/ $\times 10^{-9}$	Mn/ $\times 10^{-9}$	Sr/Ca	Ba/Ca	U/Ca	Mn/Ca
22.3290	19 580	79.23	93.32	0.19	38.91	0.004 046 48	0.004 766 08	0.000 009 61	0.001 987 23
22.818 7	10 680	30.96	6.55	0.03	124.10	0.002 898 88	0.000 613 02	0.000 002 46	0.011 619 85
23.078 7	18 730	57.98	14.94	0.08	96.30	0.003 095 57	0.000 797 65	0.000 004 52	0.015 819 54
23.140 5	18 450	34.65	3.13	0.22	61.73	0.001 878 04	0.000 169 38	0.000 011 79	0.003 345 80
23.208 6	18 680	2462	1829	0.98	236.30	0.131 798 71	0.097 912 21	0.000 052 65	0.012 649 89
23.728 5	14 510	30.46	6.14	0.38	68.86	0.002 099 24	0.000 423 29	0.000 026 06	0.004 745 69
24.051 2	10 040	18.29	13.09	0.16	38.09	0.001 821 71	0.001 303 79	0.000 016 25	0.003 793 83
24.572	9 472	38.17	3.66	0.32	63.98	0.004 029 77	0.000 386 09	0.000 034 08	0.006 754 65
24.853 4	12 370	9342	4676	0.09	39.96	0.755 214 23	0.378 011 31	0.000 007 41	0.003 230 40
25.492 6	4 801	22.22	3.88	0.07	41.39	0.004 628 20	0.000 807 12	0.000 014 30	0.008 621 12
25.632 4	21 480	87.44	16.55	0.24	71.44	0.004 070 76	0.000 770 48	0.000 011 36	0.003 325 89
25.893 2	12 030	58.99	20.60	0.50	66	0.004 903 57	0.001 712 39	0.000 041 57	0.005 486 28
26.441 6	15 090	43.63	8.71	0.08	285.40	0.002 891 32	0.000 576 93	0.000 005 61	0.018 913 19
26.715 7	8 317	23.84	6.99	0.08	203.70	0.002 866 41	0.000 839 85	0.000 009 85	0.024 492 00
27.937 5	7 973	4.16	1.39	0.10	8.33	0.000 521 39	0.000 175 21	0.000 011 98	0.001 045 28
28.3470	28 040	79.4	15.76	0.58	196.70	0.002 831 67	0.000 562 05	0.000 020 61	0.007 014 98

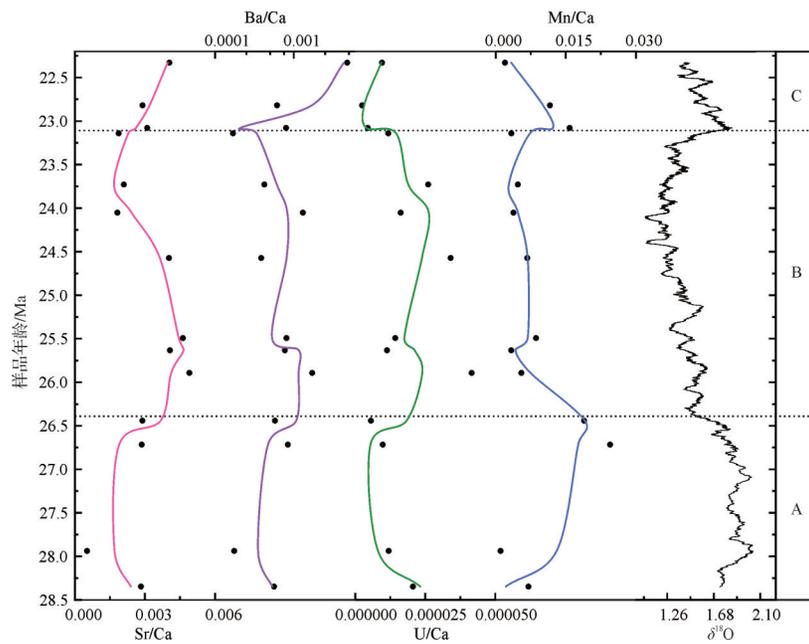


图5 上干柴沟组中上段介壳微量元素比值随年龄变化及同期深海氧同位素 ($\delta^{18}\text{O}$ 据 Cramer *et al.*^[38])
 Fig.5 Variation with age of trace element ratios for ostracod shells, upper-middle section of Upper Ganchaigou Formation, and synchronous deep-sea oxygen isotopes ($\delta^{18}\text{O}$ after Cramer *et al.*^[38])

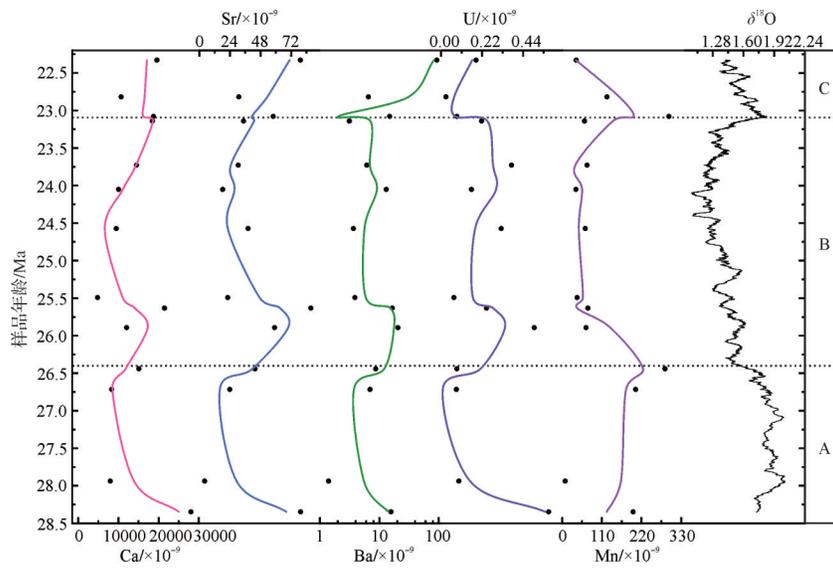


图6 上干柴沟组中上段介壳元素随年龄变化及同期深海氧同位素 ($\delta^{18}\text{O}$ 据 Cramer *et al.*^[38])
 Fig.6 Variation with age of trace elements in ostracod shells, upper-middle section of Upper Ganchaigou Formation and synchronous deep-sea oxygen isotopes ($\delta^{18}\text{O}$ after Cramer *et al.*^[38])

表2 上干柴沟组中上段各阶段介壳微量元素比值平均值

Table 2 Average values of trace elements and ratios in ostracod shells, upper-middle section of Upper Ganchaigou Formation

阶段	Ca/ $\times 10^{-9}$	Sr/ $\times 10^{-9}$	Ba/ $\times 10^{-9}$	U/ $\times 10^{-9}$	Mn/ $\times 10^{-9}$	Sr/Ca	Ba/Ca	U/Ca	Mn/Ca
C	16 330	56.06	38.27	0.10	153.10	0.003 346	0.002 059	0.000 005	0.009 809
B	12 969	41.46	9.58	0.27	58.78	0.003 347	0.000 796	0.000 022	0.005 153
A	14 885	37.76	8.21	0.21	173.53	0.002 278	0.000 539	0.000 012	0.012 866

4 讨论

4.1 柴西上干柴沟组中上段介壳微量元素古环境意义

4.1.1 介壳 Sr/Ca、Ba/Ca、U/Ca、Mn/Ca 与古环境

前人^[3,6,8,12,39-41]通过实验室培养和现代湖泊采样研究表明,介壳 Sr/Ca 主要由湖水 Sr/Ca 和盐度决定,并与盐度呈正相关性。属种差异对微量元素可能存在生物效应,胡广等^[42]研究表明属种差异对介壳 Sr/Ca 影响不大,所以本次介壳虽不是单一属种,但不影响介壳 Sr/Ca 进行古盐度重建。Ba 和 Sr 在元素周期表中属同一主族且位置相邻,它们表生化学性质相近, Yang *et al.*^[51]和 Börner *et al.*^[6]研究表明介壳 Ba/Ca 与 Sr/Ca 有很高的相关性,也可作为重建湖泊古盐度的指标。结合介壳 Sr/Ca 和 Ba/Ca,可以提高古盐度重建的可靠性,此次介壳 Sr/Ca 和 Ba/Ca 总体变化趋势相似(图 5), A 阶段 Sr/Ca 和 Ba/Ca 总体为低值,平均值均最低,表明古湖盐度较低; B 阶段 Sr/Ca 和 Ba/Ca 平均值均高于 A 阶段,表明整体上古盐度升高,在 B 阶段末 Sr/Ca 和 Ba/Ca 均有所下降,表明古盐度有所降低; C 阶段, Sr/Ca、Ba/Ca 明显上升,表明古盐度又明显升高。

介壳 U/Ca 可作为指示湖泊氧化还原状况和湖水垂直混合程度的指标,一般 U/Ca 高值指示湖水垂直混合良好的氧化环境,而低值指示高湖面还原环境^[5,43-44]。介壳 Mn/Ca 也可作为指示湖泊氧化还原状况的指标,其高值指示还原环境^[6]。本次研究介壳 Mn/Ca 变化趋势与 U/Ca 相反(图 5),与 Kim *et al.*^[44]研究结果一致。结合介壳 U/Ca 和 Mn/Ca 可以更好反演古湖的氧化还原状况: A 阶段, U/Ca 整体为低值,并有轻微下降趋势,平均值低于 B 阶段,而 Mn/Ca 平均值高于 B 和 C 阶段,有明显上升趋势,表明古湖为还原环境; B 阶段, U/Ca 整体为高值,平均值最高, Mn/Ca 整体为低值,平均值最低,表明古湖整体为氧化环境, U/Ca 在 B 阶段末有所下降,表明古湖氧化性有所减弱; C 阶段, U/Ca 明显上升, Mn/Ca 明显下降,表明古湖还原性降低而氧化性增强。

4.1.2 介壳 Sr、Ba、U、Mn 与古环境

本次研究介壳 Ca 三个阶段的平均值变化与 Sr、Ba、U、Sr/Ca、Ba/Ca 等不一致(表 2)。Bridgwater *et al.*^[41]和曾承等^[45]研究表明,较封闭湖泊体系中 Ca^{2+} 浓度与盐度不协同变化, CaCO_3 沉淀使其浓度随盐度升高变化不大,因而介壳 Ca 一般不能作为重建古盐度的指标。

通过相关性分析(图 7), Ba、U、Mn 分别与 Ba/Ca、U/Ca、Mn/Ca 有较好的相关性,相关性系数 R^2 分别为 0.94、0.6 及 0.66,表明它们有相似的环境意义。介壳 Sr 和 Sr/Ca 相关性较差,相关性系数 R^2 为 0.3,但 Sr 总体变化趋势和各阶段平均值变化特征与 Ba、U、Ba/Ca、U/Ca 等一致,因此也可进行古环境意义探讨。

内陆湖水中 Sr 元素含量的增加是干旱炎热气候下湖水蒸发浓缩的结果^[46-47],介壳 Sr 直接来源于宿生水体,前人研究^[48-50]表明在较高盐度和少营养水体中以介壳 Sr 的高含量为特征, Ba 在介壳中的变化与 Sr 有同样的机理^[5]。介壳 Sr、Ba 值在 A 阶段平均值最低,均从开始的较高值下降为低值阶段,表明古湖向低盐度演化; B 阶段 Sr、Ba 的平均值都高于 A 阶段,表明古湖盐度整体高于 A 阶段, Sr、Ba 值在 B 阶段末有所降低,表明古盐度有所下降; C 阶段 Sr、Ba 值明显上升,表明古湖盐度又明显升高。总体上介壳 Sr、Ba 得出的盐度演化特征与 Sr/Ca、Ba/Ca 得出的结论基本一致。

U 和 Mn 对水体的氧化还原性很敏感, U 一般在氧化水体中呈溶解态而在还原水体中不溶解^[6], Mn 在缺氧水体中以稳定形式存在且高值指示还原环境^[51-52],一般介壳在少盐水和较还原的水体中 Mn 含量较高^[48-50]。A 阶段 U 值从开始较高值下降为低值阶段, Mn 整体为高值,表明古湖向还原环境演化; B 阶段 U 整体为高值,平均值最高, Mn 整体为低值,平均值最低,表明古湖整体为氧化环境; C 阶段 U 呈上升趋势,而 Mn 呈明显下降趋势,表明古湖氧化性又开始增强。总体上介壳 U、Mn 所得出的古湖各阶段的氧化还原性特征与 U/Ca、Mn/Ca 得出的结论基本一致。

综合上述各阶段介壳 Sr/Ca、Ba/Ca、Sr、Ba 值指示的古盐度特征及 U/Ca、Mn/Ca、U、Mn 值指示的氧化还原性特征,柴达木盆地西部上干柴沟组中上段(28.35~22.33 Ma)古湖环境演化特征为: A 阶段(28.35~26.42 Ma),古湖盐度较低,还原性较强,盐度和氧化还原性与内陆湖泊水位变化密切相关,水位上升必然会导致湖泊平均含盐量的下降和还原性的增强^[40,53],表明该阶段为高水位深湖环境; B 阶段(26.42~23.08 Ma),古湖盐度整体较高,氧化性较强,表明为低水位浅湖环境,盐度和氧化性在 B 阶段末有所下降,表明水位有所上升; C 阶段(23.08~22.33 Ma),古湖盐度升高,氧化性增强,表明湖水又开始变浅。

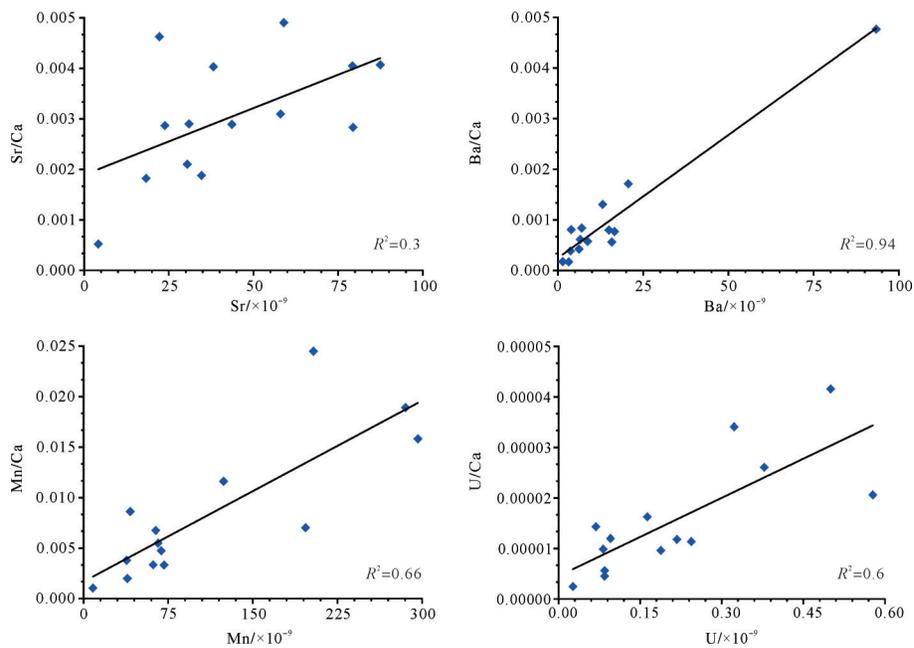


图7 上干柴沟组中上段介壳微量元素与比值相关性

Fig.7 Correlation between trace elements and ratios in ostracod shells from the upper-middle section, Upper Ganchaigou Formation

三个阶段的古湖环境演化特征与前面通过岩性和沉积构造得出的古湖沉积相的演化阶段特征相对应(图4)。

4.2 柴西上干柴沟组中上段介壳微量元素古气候意义

对较封闭内陆湖泊而言,湖区有效降水率P/E(降水量/蒸发量)和入湖径流量Q是影响水位变化的主要因素,而水位变化直接影响湖水水化学、盐度及氧化还原状况^[45,53-54],一般流域气候湿润时,湖区P/E和Q增大,致使湖泊水位上升,湖水离子浓度和盐度下降,湖水整体上还原性增强;反之,流域气候变得干旱时,湖区P/E和Q减小,致使湖泊水位下降,湖水离子浓度和盐度升高,湖水整体上氧化性增强。介形虫对上述水位变化引起的水化学、盐度等环境要素的变化极为敏感^[55],而且在其建造新壳的过程中直接从宿生水体中摄取化学元素^[7,10,12],所以介壳微量元素可作为湖泊古水体参数的代替指标,进而反演湖区古气候演化。随着新生代青藏高原隆起,周缘山脉的隆升致使柴达木盆地第三系为内陆凹陷湖盆^[29],而且柴达木盆地西部上干柴沟组沉积期古湖为内陆沉积盆地^[56],因而水位变化主要受周围汇聚于古湖古水系和流域降水的影响。

综合前述各阶段介壳微量元素指示的柴达木盆地西部上干柴沟组中上段古湖古环境演化特征,A阶段(28.35~26.42 Ma),古湖水位较高,表明湖区P/E和

Q增大,进一步表明古气候较为湿润;B阶段(26.42~23.08 Ma),古湖整体上湖水变浅,表明湖区P/E和Q减小,进一步表明气候整体相对干旱,在B阶段末水位有所上升,表明气候干旱程度降低;C阶段(23.08~22.33 Ma),古湖水位又开始下降,表明湖区P/E和Q开始减小,进而表明湖区气候又向干旱演化。

4.3 柴西上干柴沟组中上段介壳化石古环境古气候意义

除介壳地球化学外,介壳化石古生态也是一种重建古环境的有效方法,两者结合可以达到更理想的效果^[11-12],介壳化石及其组合的生态特征可以提供湖泊水化学、盐度及水文等方面的信息^[2,57]。在前述介壳微量元素比值Sr/Ca、Ba/Ca、U/Ca、Mn/Ca及元素Sr、Ba、U、Mn变化的三个阶段A、B及C,介壳化石(*Eucypris*、*Youshashania*及*Hemicyprinotus*)有不同的组合特征,结合化石及其组合的生态属性和所指示的环境特征(表3),可进一步在介壳微量元素分析基础上探讨各个阶段的古环境古气候演化。

由表3可知,在A阶段是单一*Eucypris*组合,指示少盐水或更高盐度湖泊环境,*Eucypris*一般生活在淡水和少盐的水体中,也可在更高盐度湖泊中出现^[58-60],这与前述通过介壳微量元素所得出的A阶段古湖为盐度较低且还原性较强的结论不矛盾;B阶段为*Youshashania*-*Hemicyprinotus*-*Eucypris*组合,指示多

表3 上干柴沟组中上段各阶段化石组合及指示环境特征(据青海石油勘探开发研究院和中科院南京古生物研究所^[17]; 杨平等^[58];柳祖汉等^[59];吉利明等^[60];杨藩等^[61])

Table 3 Ostracod shell fossil assemblages and indicative environmental characteristics in the upper-middle section of Upper Ganchaigou Formation(after Qinghai Petroleum Exploration and Development Research Institute and Nanjing Institute of Paleontology, Chinese Academy of Sciences^[17]; Yang *et al.*^[58]; Liu *et al.*^[59]; Ji *et al.*^[60]; Yang *et al.*^[61])

阶段	介壳化石组合	环境指示意义
C	<i>Hemicyprinus-Eucypris</i> 组合	少盐水—真盐水或更高盐度河口或湖泊近岸浅水
B	<i>Youshashania-Hemicyprinus-Eucypris</i> 组合	多盐水—真盐水或更高盐度干旱—半干旱滞水或较封闭浅湖
A	单一 <i>Eucypris</i> 组合	一般为少盐水或更高盐度湖泊

注:此次采用威尼斯分类的盐度划分标准,淡水 0~0.5‰,少盐水 0.5‰~5‰,中盐水 5‰~18‰,多盐水 18‰~30‰,真盐水 30‰~40‰,超盐水 >40‰。

盐水—真盐水或更高盐度干旱—半干旱滞水或封闭浅湖环境,相比于 A 和 C 阶段,该阶段化石组合中出现了 *Youshashania*,它是生活在多盐水—真盐水或更高盐度较干旱环境下的喜盐属^[16,58-59],同时也出现了 *Hemicyprinus*,它生活在少盐水—真盐水河口或湖泊近岸半氧化浅水环境^[16,61],表明该阶段古湖整体盐度较高和氧化性较强,水位较低,气候较干旱,这与介壳微量元素得出的结论一致;C 阶段为 *Hemicyprinus-Eucypris* 组合,指示少盐水—真盐水或更高盐度河口或湖泊近岸浅水,该阶段主要以 *Hemicyprinus* 为主,表明古湖开始萎缩,湖水变浅,与前述介壳微量元素表明的该阶段古湖水位下降,气候变干旱的结论基本一致。

4.4 柴西上干柴沟组中上段古气候演化及影响因素

前述通过介壳微量元素和化石组合特征古环境古气候分析表明,柴达木盆地西部上干柴沟组中上段(28.35~22.33 Ma)古气候主要有三个阶段的演化特征,A 阶段(28.35~26.42 Ma),古气候较为湿润;B 阶段(26.42~23.08 Ma),古气候整体相对干旱,在末段干旱程度有所缓解;C 阶段(23.08~22.33 Ma),古气候又向干旱演化。

通过介壳微量元素与全球深海氧同位素的对比(图 5,6),古气候较为湿润的 A 阶段对应的深海 $\delta^{18}\text{O}$ 较高,全球气温相对偏低,但当时青藏高原整体古海拔不是很高^[62],柴达木盆地西部古海拔也大约只有 1 500 m^[6],所以当时气温不会很低,而据 Song *et al.*^[63]柴达木盆地 30~26.42 Ma 化学风化指标为开始持续增加和后续为稳定的高值,表明该阶段气候向暖湿演化,综合表明 28.35~26.42 Ma,柴达木盆地西部气候为相对温暖湿润;古气候整体相对干旱的 B 阶段对应的深海 $\delta^{18}\text{O}$ 较低,为晚渐新世暖期^[38,64],洪汉烈等^[65]通过黏土矿物学特征表明柴达木盆地~26.5 Ma

的升温事件与全球气候演化相一致,而 Sun *et al.*^[66]研究表明此期间柴达木盆地周围植被主要以稀释草原为主且气候干热,表明 26.42~23.08 Ma,柴达木盆地西部气候总体以炎热干旱为特点,本次研究表明在 B 阶段末气候干旱程度有所降低;古气候向干旱演化的 C 阶段对应深海 $\delta^{18}\text{O}$ 较高,特别是 23.08 Ma 对应渐新世—中新世界限处 Mi-1 冰期事件^[38,64],表明全球气候又开始变冷,张克信等^[67-68]认为约 23 Ma 青藏高原不整合面广布,标志青藏高原的整体隆升,青藏高原南部的冈底斯和喜马拉雅在早中新世也有明显的构造抬升^[69],表明早中新世全球气候变冷、青藏高原隆升对柴达木盆地西部气候影响较大,23.08~22.33 Ma,柴达木盆地西部气候变冷干。而其西南边的沱沱河盆地,东南边的青海循化盆地及兰州盆地在约 23 Ma 也开始变得干旱^[70-72],Xu *et al.*^[37]的研究也表明从 23 Ma 年开始青藏高原东北缘是干旱的气候条件,表明早中新世整个中国西北内陆干旱化开始。自~34 Ma 副特提斯海从塔里木盆地西南退出^[73-74],并不断向西退缩,导致中亚陆地面积增加和西风环流带来的水汽减少^[75],特别是晚渐新世—早中新世其面积的向西缩减是亚洲内陆干旱化形成的重要原因之一^[76],所以副特提斯海的西退对上述柴达木盆地西部各阶段的气候演化也有一定影响。

5 结论

通过分析柴达木盆地西部上干柴沟组中上段(28.35~22.33 Ma)介壳微量元素比值 Sr/Ca、Ba/Ca、U/Ca、Mn/Ca 及元素 Sr、Ba、U、Mn 变化特征及介壳化石(*Eucypris*、*Youshashania*、*Hemicyprinus*)组合特征,并结合同期全球深海氧同位素及前人研究成果,我们得出以下结论:

(1) 柴西上干柴沟组中上段介壳微量元素有明显

的 A (28.35~26.42 Ma)、B (26.42~23.08 Ma) 及 C (23.08~22.33 Ma) 三个阶段的变化特征,介壳微量元素比值 Sr/Ca、Ba/Ca、U/Ca 及元素 Sr、Ba、U 在 A 阶段值较低,B 阶段值整体较高,段末值有所下降,C 阶段值明显上升,Mn/Ca 和 Mn 值变化大致相反。相应各阶段的介壳化石组合分别为单一 *Eucypris* 组合、*Youshashania-Hemicyprinus-Eucypris* 组合及 *Hemicyprinus-Eucypris* 组合。

(2) 柴西上干柴沟组中上段古湖古环境主要经历了三个阶段的演化特征:A 阶段,古湖为盐度较低和还原性较强的高水位深湖环境;B 阶段,古湖整体为盐度较高和氧化性较强的浅湖环境,在该阶段末盐度和氧化性有所下降,水位有所上升;C 阶段,古湖盐度和氧化性又明显升高,湖水变浅。

(3) 柴西上干柴沟组中上段古气候主要经历了三个阶段的演化特征:A 阶段,古气候相对温暖湿润;B 阶段,古气候整体炎热干旱,在该阶段末干旱程度下降;C 阶段,古气候向冷干演化,响应了早中新世中国西北内陆干旱化。该地质时段古气候演化主要受全球气候演化和青藏高原隆升的影响,与副特提斯海西退也有一定关系。

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Paleoenvironmental and Paleoclimatic Significance of Trace Elements in Ostracod Shells in the Upper-Middle Section, Upper Ganchaigou Formation, Western Qaidam Basin

CHEN Wei^{1,2}, LI Xuan^{1,2}, ZENG Liang^{1,2}, WANG QingTong^{1,2,3}, JIAO XueYao^{1,2}, YANG Ping⁴,
JIANG XiaoQing⁴, MA JinLong^{1,2}

1. College of Earth Sciences, Lanzhou University, Lanzhou 730000, China

2. Key Laboratory of Mineral Resources in Western China (Gansu Province), Lanzhou 730000, China

3. The 7th Gold Detachment of Chines Armed Police Force, Yantai, Shandong 264004, China

4. Research Institute of Petroleum Exploration and Development, PetroChina Qinghai Oilfield Company, Dunhuang, Gansu 736202, China

Abstract: Trace elements in ostracod shells in sedimentary deposits have important significance for studies of the paleoclimate and paleoenvironment. Variation in trace element content in ostracod shells combined with the characteristics of the ecological environment of ostracod fossil assemblages yielded more details about the paleoenvironmental and paleoclimatic evolution during the middle-upper section of Upper Ganchaigou Formation in the western Qaidam Basin. The trace element ratios Sr/Ca, Ba/Ca and U/Ca, and the trace amounts of Sr, Ba and U in the ostracod shells were low in phase A (28.35-22.33 Ma); their values were high in phase B (26.42-23.08 Ma), declining at the end of this phase. In phase C (23.08-22.33 Ma) they increased significantly, although the Mn/Ca ratio and Mn content showed approximately the opposite change. The average values of Sr/Ca and Sr (respectively $0.002\ 278$ and 37.76×10^{-9}) were low in phase A and higher in phase B (respectively $0.003\ 347$ and 41.46×10^{-9}), and their average values were also higher in phase C (respectively $0.003\ 346$ and 56.06×10^{-9}). The average values of Ba/Ca, U/Ca, Ba and U changed similarly, whereas the average values for Mn/Ca and Mn showed opposite changes. The ostracod shell assemblages also differed in the corresponding phases. Combining these trace element variations in the ostracod shell fossils and their assemblages with synchronous deep-sea oxygen isotopes, and noting previous research results, the evolution of the paleoenvironment and paleoclimate in the middle-upper section of Upper Ganchaigou Formation was determined to be the following. In phase A, the ancient lake of the western Qaidam Basin was a deep, low-salinity, strongly reducing lake environment with high water level; the climate was relatively warm and moist. In phase B, the lake was shallow, with high salinity, strongly oxidizing and low water level, and the overall climate was hot and arid. At the end of phase B, the salinity and oxidizing properties of the lake water decreased as the water level rose, and the climate became less arid. In phase C, the salinity and oxidation of the lake water increased as the water level fell, and the climate became cold and arid, similar to the inland aridity of northwestern China in the early Miocene. The paleoclimate during this geological period was mainly influenced by global climate evolution and uplift of the Tibetan Plateau, and also the retreat of the Paratethys Sea to the west.

Key words: Qaidam Basin; Upper Ganchaigou Formation; ostracods; trace elements; paleoenvironment