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青海湖东岸全新世风成沉积地球化学特征及其古气候意义

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摘要 青海湖地区因独特的地理位置, 其古气候演化一直为学者们所关注。由于各类环境替代指标的多解性, 以往研究中对青海湖地区末次冰消期以来特别是早全新世的气候特征存在不一致的认识。对青海湖东岸种羊场风成沉积物的元素地球化学特征及其古气候意义进行分析, 结合磁化率、粒度和色度指标重建了过去约11 ka 青海湖地区古气候演变过程。结果表明: 1) 化学蚀变指数(CIA)值和 $Al_2O_3-(CaO+Na_2O)-K_2O$ (A-CN-K)三元图指示种羊场风成沉积经历了弱风化、中等程度的风化强度。CIA值的波动变化反映青海湖地区全新世期间经历了较大的干湿变化。2) 亮度(L^*)与总有机碳(TOC)含量呈高度负相关($R^2=0.71$, $P<0.01$), 可以间接地反映研究区古气候演变过程。3) 种羊场(ZYC)剖面的多指标分析结果和剖面地层特征揭示青海湖地区在11.0~6.5 ka B.P. 时期, 风化作用较弱, 气候可能相对温暖干旱; 6.5~1.1 ka B.P. 时期风化作用可能较强, 为暖湿期, 与古湖岸堤记录的湖面变化较为一致; 1.1 ka B.P. 至今, 气候变得干旱。4) 亚洲季风和太阳辐射的强弱变化可能造成有效湿度的高低变化, 从而导致青海湖地区全新世气候干湿交替变化。

关键词 青海湖; 全新世; 元素地球化学; 风成沉积; 古气候变化

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0 引言

青海湖地区位于中国东部季风湿润区、西北干旱区和青藏高原高寒区的过渡带, 对气候变化的响应敏感^[1]。青海湖地区因其独特的地理位置和气候条件, 成为人们了解过去气候和环境演变过程的重要窗口。

过去关于青海湖地区环境和气候演变的研究主要集中在湖相沉积和风成沉积(黄土、古土壤及风成砂)^[2-7]。然而, 由于各类环境替代指标的多解性导致重建的末次冰消期以来特别是早全新世的气候特征存在不一致的认识^[5,8]。一些研究认为全新世早期气候温干、湖面较低、水体含盐量较高^[3,5,9], 而另一些研

究认为早全新世气候暖润、湖面比现在高、水体含盐量较低^[2,4,10]。

青海湖地区的风成沉积研究也存在认识上的差异。基于光释光(Optically Stimulated Luminescence, OSL)定年技术, Liu *et al.*^[11]对青海湖湖面变化过程的研究揭示早全新世湖面相对较低; 中全新世湖面逐渐上升, 在5 ka B.P. 左右出现最高湖面; 晚全新世湖面趋于下降。上述湖面变化过程与利用多个湖东风成沉积剖面重建的古气候演变过程可以相互印证^[1,7,12], 但与南岸哈拉力剖面^[13]早全新世期间发育古土壤的温湿气候存在认识上的差异。因此, 青海湖地区的古气候演变过程仍值得进一步研究。

虽然对青海湖地区风成沉积的地球化学特征及

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利用其重建古气候信息的工作已有报道^[1,6-7,14],但是利用这套沉积的地球化学相关指标与磁化率、粒度、色度等指标结合来重建古气候变化的研究仍然较少。在前期 OSL 定年建立了剖面年代框架的基础上^[15-16],本研究对青海湖地区种羊场剖面(简称为 ZYC 剖面)风成沉积物的元素地球化学特征及其古气候意义进行分析,并结合磁化率、粒度和色度指标,旨在重建青海湖地区全新世期间古气候演变过程,对驱动其气候变化的机制进行初步探讨。

1 研究区概况

青海湖位于青藏高原东北部,是我国最大的内陆高原咸水湖泊。湖区为大通山、日月山、青海南山、橡皮山等山脉所环绕(图 1a)。湖水的补给主要来自北部和西北部的河流,其中布哈河的补给量约占总补给量的 50%^[17]。

青海湖地区的气候属半干旱内陆温带大陆性气候,夏季时东亚夏季风可渗入到该地区^[2];湖区年平均温度约为 1.2℃;年均降水量为 400 mm,60% 的降水集中在 6—9 月^[18]。湖区周边呈环带状广泛分布风成沉积,以黄土和风成砂为主。研究区的主要植被类型为半干旱—干旱和高寒地区所特有的高寒草甸、高寒草原和高寒灌丛等^[19]。

2 材料与方法

2.1 剖面 and 样品采集

ZYC 剖面的经纬度为 36.63° N, 100.87° E, 海拔 3 390 m(图 1a, b)。该剖面总采样厚度为 120 cm,从顶至底依次为:0~30 cm,灰色砂质土壤层,现代植物

根系丰富;30~80 cm,灰色粉砂质古土壤层,植物根系较少,结构致密;80~100 cm,灰黄色粉砂质黄土层,较疏松;100~120 cm 为浅黄色风成砂,结构疏松,未见底。

散样样品采样间隔为 2 cm,共采集 60 个。OSL 测年样品不定间隔共采集了 6 个,其年龄分别为 0.9±0.1 ka(深 20 cm)、1.1±0.1 ka(深 30 cm)、4.9±0.4 ka(深 49 cm)、6.5±0.6 ka(深 68 cm)、8.2±0.7 ka(深 80 cm)和 10.0±1.0 ka(深 107 cm)^[15-16]。OSL 年龄与地层层序分布一致。假定剖面顶部的年代为 0 ka,依据剖面的 OSL 年龄采用线性内插和外推的方法,计算出剖面各深度的沉积年龄,剖面底部(深 120 cm)的年代约为 11 ka,黄土层与风成砂层过渡处(深 100 cm)年代约为 9.54 ka。

2.2 指标分析

样品自然风干之后用于实验分析。主、微量元素含量测试:样品在玛瑙研钵中充分磨细,并使其通过 200 目不锈钢网筛,采用压片法测定元素的含量,仪器为荷兰帕纳科公司生产的 Axios X 射线荧光光谱仪,各元素分析误差小于 10%。

磁化率的测试采用英国 Bartington MS2 型双频率磁化率仪完成,具体测试过程与曾方明等^[20]描述一致。粒度样品经过去除有机质和碳酸盐之后采用激光粒度仪 Malvern Mastersizer 2000 进行颗粒粒径的测试。磁化率和粒度数据见已发表文章^[21]。

色度用 CIE1976 L*、a*、b* 表色系统进行表示,L* 代表亮度,变化于黑(0)与白(100)之间,表示土壤的明暗程度;a* 代表红度,变化于红绿之间;b* 代表黄度,变化于黄蓝之间^[22]。色度测试在日本 Konica Minolta CM2500-C 分光测色仪上进行。

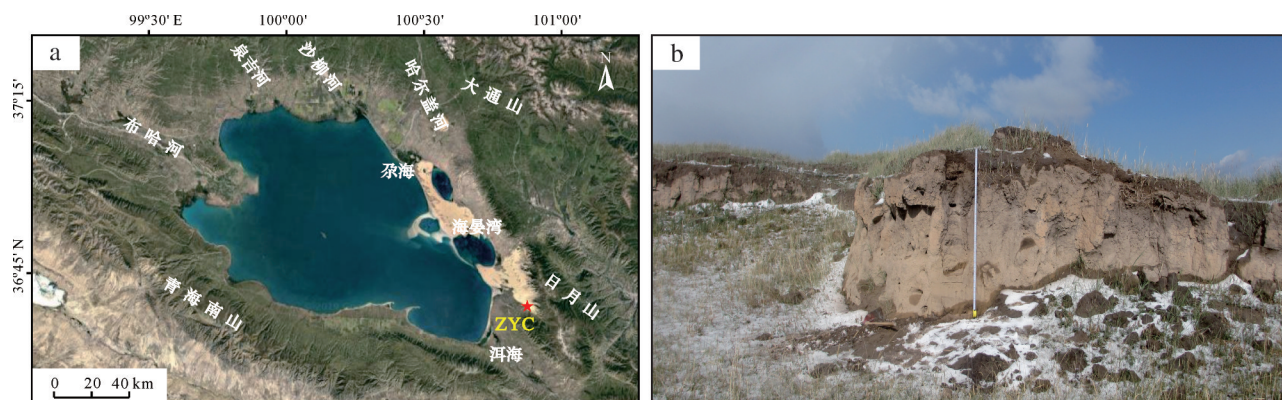


图 1 ZYC 剖面位置(a.底图来自 Google Earth)与照片(b)

Fig.1 (a) Location (base map from Google Earth) and (b) photograph of ZYC section

3 结果

3.1 种羊场风成沉积物的元素含量

种羊场风成沉积的主、微量元素组成和含量见表1。主量元素以SiO₂(平均50.43%)、Al₂O₃(平均12.03%)、CaO(平均10.21%)、Fe₂O₃(平均4.20%)、MgO(平均2.35%)、K₂O(平均2.34%)和Na₂O(平均1.56%)为主。TiO₂、P₂O₅和MnO元素含量均小于1%。种羊场风成沉积物相比于UCC(上地壳)^[23](图2a),显著富集CaO,亏损Na₂O。Fe₂O₃、TiO₂、P₂O₅和MnO含量与UCC相近,SiO₂、Al₂O₃、K₂O含量较低。微量元素UCC^[23]标准化图(图2b)显示,种羊场风成沉积物相比于UCC^[23]有显著的Nb亏损,富集V、Cr、Co、Ni、Y、Zr、La、Ba、Nd、Pb的含量接近于UCC。

3.2 磁化率、粒度和色度

风成沉积物的磁化率和粒度分别可以指示研究区降水、温度的变化及区域内风沙活动的强弱,已被

用于气候和环境演变过程的重建^[24-26]。种羊场风成沉积的磁化率和粒度数据已被Liu *et al.*^[21]报道,故本文仅做简单论述。剖面磁化率值变化范围为(17.02×10⁻⁸~70.7×10⁻⁸) m³/kg,中值粒径(*M_d*)变化范围为10.19~140.84 μm,其中古土壤层的中值粒径最小,磁化率值最高。

ZYC剖面风成砂层的亮度(L*)值较高,古土壤层L*值较低(表2),与黄土高原渭南和西峰黄土剖面^[27]及毛乌素沙漠风成沉积剖面类似^[28]。ZYC剖面风成砂层的TOC含量较低,而古土壤层的TOC含量较高^[16]。ZYC剖面L*和TOC含量^[16]呈高度负相关(*R*²=0.71, *P*<0.01,图3a),表明种羊场剖面L*主要受TOC含量变化的控制。在青藏高原东北部,研究表明沉积物中TOC含量与沉积时期的年降水量、植被覆盖程度和温度密切相关^[29]。因此,对于种羊场风成沉积物,L*可以指示区域植被覆盖程度的变化,从而间接地反映研究区古气候演变过程。

表1 ZYC剖面风成沉积物的主量元素和微量元素含量

Table 1 Major-element and trace-element concentrations of aeolian deposit samples from ZYC section

层位	砂质土壤			古土壤			黄土			风成砂			UCC ^[23]
元素	最大值	最小值	平均值	最大值	最小值	平均值	最大值	最小值	平均值	最大值	最小值	平均值	平均值
SiO ₂ /%	59.08	53.34	56.15	55.25	43.66	48.02	47.73	46.31	47.18	53.39	49.15	51.92	66
Al ₂ O ₃ /%	13.6	10.13	11.93	13.37	12.06	12.68	12.04	11.24	11.74	11.18	10.38	10.77	15.2
K ₂ O/%	2.75	2.15	2.43	2.72	2.24	2.44	2.26	2.13	2.21	2.11	2	2.05	3.4
Na ₂ O/%	1.97	1.43	1.59	1.67	1.25	1.4	1.78	1.59	1.65	1.91	1.78	1.83	3.9
CaO/%	8.87	5.48	7.42	13.81	6.23	10.81	12.33	11.88	12.04	11.57	10.24	10.74	4.2
MgO/%	2.2	1.2	1.79	2.94	2.1	2.54	2.78	2.64	2.7	2.5	2.07	2.27	2.2
Fe ₂ O ₃ /%	4.95	2.52	3.87	5.02	4.42	4.73	4.3	3.87	4.14	3.69	3.15	3.36	4.5
TiO ₂ /%	0.65	0.33	0.52	0.63	0.5	0.56	0.53	0.52	0.53	0.52	0.47	0.5	0.5
P ₂ O ₅ /%	0.26	0.14	0.2	0.2	0.16	0.18	0.19	0.18	0.18	0.18	0.14	0.15	0.16
MnO/%	0.1	0.06	0.08	0.1	0.08	0.09	0.08	0.07	0.08	0.07	0.06	0.07	0.08
V/(μg/g)	86.93	45.07	71.03	85.43	74.45	79.94	76.11	66.63	71.04	71.21	64.15	68.14	60
Cr/(μg/g)	77.93	43.98	64.9	75.25	54.34	62.09	57.41	53.03	55.06	60.19	50.76	54.95	35
Co/(μg/g)	13.36	7.95	11.13	15.73	13.85	14.87	16.84	13.67	15.28	12.78	8.61	9.87	10
Ni/(μg/g)	31.69	14.02	24.16	34.75	31.92	33.3	30.59	26.46	28.26	22.87	17.92	20.25	20
Cu/(μg/g)	24.28	11.85	19.6	28.21	23.35	25.73	24.73	21.28	23.33	16.73	12	13.81	25
Zn/(μg/g)	74.06	37.94	59.43	77.61	69.15	73.47	67.97	58.44	64.33	53.87	43.94	48.02	71
Ga/(μg/g)	17.82	12.44	13.94	17.44	13.94	15.23	14.74	12.62	13.94	13.11	12.34	12.6	17
Rb/(μg/g)	116.37	84.44	100.12	119.4	98.6	108.43	96.66	91.2	94.59	89.78	82.57	84.83	112
Sr/(μg/g)	255.19	195.77	225.97	364.08	209.5	293.44	366.75	354.64	361.74	339.73	295.26	309.11	350
Y/(μg/g)	29.67	22.54	27.7	31.45	28.95	30.17	29.49	28.14	28.85	28.33	26.58	27.2	22
Zr/(μg/g)	270.48	156.43	234.28	229.24	151.36	183.25	239.52	204.02	216.28	282.44	230.93	263.07	190
Nb/(μg/g)	15.23	8.74	12.75	15.97	11.83	13.66	13.85	11.92	12.83	12.69	11.9	12.34	25
Ba/(μg/g)	551.75	479.81	505.08	574.58	487.47	527.96	503.66	467.25	486.97	503.26	481.38	488.58	550
La/(μg/g)	53.17	26.52	37.5	58.13	24.98	43.74	52.52	36.6	41.54	59.06	13.82	34.59	30
Ce/(μg/g)	64.12	36.54	49.99	67.73	33.66	47	69.97	35.31	50.82	66.26	29.7	47.88	64
Nd/(μg/g)	36.54	17.26	25.94	41.54	18.96	27.03	25.28	20.44	22.86	23.94	16.64	20.61	26
Pb/(μg/g)	24.51	16.67	19.99	23.89	18.74	21.28	20.64	14.4	17.75	17.59	14.34	15.7	20

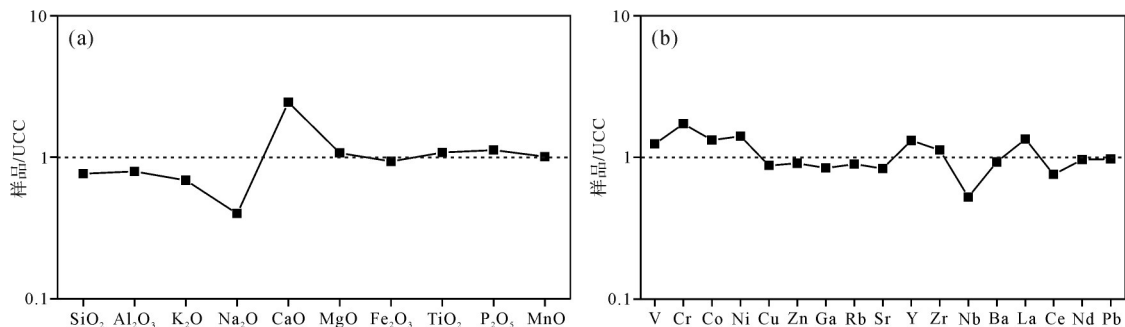


图2 ZYC剖面风成沉积物主量元素(a)和微量元素(b)UCC^[23]标准化图

Fig.2 UCC^[23]-normalized abundances of elements for the aeolian deposit samples from the ZYC section(a) major elements; (b) trace elements

表2 ZYC剖面风成沉积物色度测试结果

Table 2 Color parameters of aeolian deposits from ZYC section

深度/cm	L*	a*	b*	深度/cm	L*	a*	b*
2	51.70	5.41	15.55	62	55.69	4.52	13.58
4	48.17	5.32	14.50	64	59.19	4.45	13.94
6	48.55	5.29	14.37	66	58.77	4.62	14.29
8	48.15	5.22	14.16	68	57.79	4.60	14.17
10	50.21	5.27	14.42	70	55.69	4.85	13.99
12	49.97	5.50	14.87	72	57.04	4.63	14.19
14	49.05	5.55	15.10	74	57.77	4.57	14.08
16	50.08	5.62	15.47	76	55.17	4.73	14.26
18	49.66	5.86	15.83	78	55.39	4.82	14.48
20	49.98	5.82	15.52	80	53.59	4.86	14.05
22	50.12	5.70	15.24	82	56.25	4.75	14.41
24	49.27	5.78	15.29	84	56.65	4.67	14.44
26	48.40	5.85	15.27	86	57.22	4.80	14.85
28	46.69	5.95	15.19	88	55.94	4.85	14.90
30	45.77	5.95	14.96	90	56.30	4.96	14.82
32	46.93	5.93	15.13	92	56.42	4.73	14.64
34	47.41	5.79	14.87	94	59.08	4.83	15.33
36	47.82	5.63	14.75	96	56.82	5.04	15.44
38	47.37	5.44	14.38	98	56.88	4.90	15.17
40	48.93	5.12	13.91	100	58.88	4.97	15.48
42	45.11	4.91	12.89	102	63.02	4.46	15.34
44	48.39	4.95	13.50	104	63.37	4.34	15.04
46	46.87	4.92	13.38	106	62.62	4.38	15.03
48	47.70	4.82	13.11	108	63.99	4.37	15.55
50	51.48	4.78	13.24	110	66.63	4.02	15.43
52	50.11	4.79	13.55	112	67.46	3.97	15.61
54	53.90	4.26	12.84	114	65.73	4.19	15.65
56	53.13	4.38	13.01	116	65.92	4.24	15.61
58	57.86	4.26	13.21	118	65.66	4.42	16.08
60	60.50	4.55	14.00	120	65.48	4.71	16.52

ZYC剖面总体上在古土壤层与砂质土壤层的过渡处a*值最高,风成砂层的a*值最低,a*值自风成砂层至砂质土壤层有增高的趋势(表2、图3c)。黄土高原渭南和西峰黄土剖面(不考虑渭南剖面L₂/S₁过渡地层)的a*与磁化率之间具有很强的相关性,且a*的变化被认为与风化成壤作用密切相关^[27]。但是,ZYC剖面的a*与磁化率之间不相关(R²=0.01,P=0.42,图3b)。然而,控制种羊场风成沉积a*变化的因素有待进一步探究。因此,在重建青海湖地区古气候和环境演变过程时具有局限性,需谨慎使用。

3.3 ZYC剖面风成沉积物的元素比值及古气候意义

通常利用CIA(chemical index of alteration,CIA=[Al₂O₃/(Al₂O₃+CaO*+Na₂O+K₂O)]×100,化学蚀变指数,摩尔数)来评价沉积物的化学风化程度^[30],并利用Al₂O₃-(CaO*+Na₂O)-K₂O(A-CN-K)三元图(各氧化物为摩尔数)^[31]来推断沉积物的风化趋势,其中CaO*指硅酸盐中CaO的含量。本次研究按照文献^[32]所描述的方法进行了磷酸盐的校正并估算了硅酸盐中CaO的含量。

风化程度的强弱与气候和环境的变化密切相关,通常化学风化程度的增强与较高的温度和降水有关,反之亦然^[30]。已有研究表明,CIA值从低到高依次代表未风化(<50)、弱风化(50~60)、中等风化(60~80)和强风化(>80)(图4)^[33]。种羊场风成沉积的CIA值变化范围为53.49~65.60,平均值为61.08(图4),低于西宁全新世黄土(CIA=68.8,YJC剖面,未发表数据)。在不同的地层单元中(图5),古土壤的CIA值最高,表明古土壤在相对湿热的气候条件下经历了较强的化学风化作用,而底部风成砂和黄土的CIA值较低,指示两者可能在相对干燥的气候状态下遭受了较弱的化学风化作用。种羊场风成沉积CIA

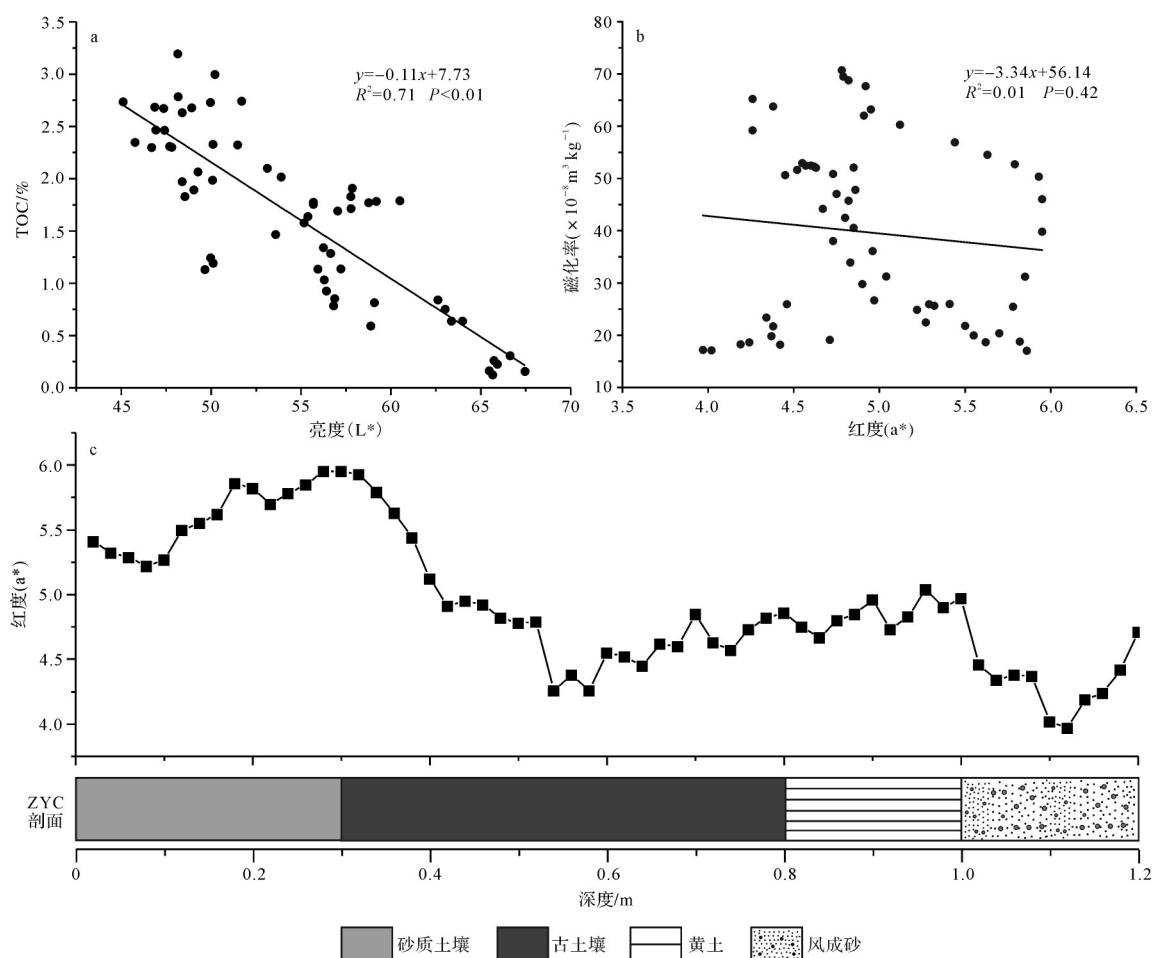


图3 ZYC剖面风成沉积物亮度(L^*)与TOC含量^[16](a)和红色(a^*)与磁化率(b)的相关性分析及(c)红色(a^*)变化特征
Fig.3 Correlations between (a) lightness and TOC content^[16]; (b) redness and magnetic susceptibility; and (c) variation of redness of aeolian deposit samples from ZYC section

值显示种羊场风成沉积经历了弱风化、中等程度的化学风化强度,其波动变化反映青海湖地区全新世期间经历了较大的冷暖、干湿交替。

A-CN-K三元图(图4)显示种羊场风成沉积与预测的从UCC到PAAS(Post-Archean Australian Shale)的风化趋势线一致^[31],靠近斜长石一侧,与A-CN轴平行,表明种羊场风成沉积仍处于斜长石风化早期Ca和Na的去除阶段。

在气候变化影响下,根据相对稳定元素和易迁移元素的不同地球化学行为,学者们提出了Rb/Sr比值、 $(\text{CaO}+\text{Na}_2\text{O}+\text{MgO})/\text{Ti}_2\text{O}$ 比值(各氧化物为摩尔数)来重建古气候变化,较高的Rb/Sr比值和较低的 $(\text{CaO}+\text{Na}_2\text{O}+\text{MgO})/\text{Ti}_2\text{O}$ 比值可指示相对湿热的气候条件^[39-40]。种羊场风成沉积的Rb/Sr比值变化范围为0.26~0.57,平均值为0.36,古土壤层具有较高的Rb/Sr比值(图5f),对应古土壤层较高的CIA值(图5i)。

$(\text{CaO}+\text{Na}_2\text{O}+\text{MgO})/\text{Ti}_2\text{O}$ 比值(图5g)变化范围为21.80~53.43,平均值为40.06,变化趋势与Rb/Sr比值和CIA值相反。值得注意的是,Rb/Sr比值、 $(\text{CaO}+\text{Na}_2\text{O}+\text{MgO})/\text{Ti}_2\text{O}$ 比值与CIA值峰值位置明显不同,可能与不同指标对气候变化响应的敏感程度不同有关。

4 讨论

综合ZYC剖面地球化学相关指标、粒度、磁化率及色度和剖面地层特征,并与其它古气候替代指标作比较(图5),我们对青海湖地区气候演变过程进行分析,初步认为青海湖地区11.0 ka B.P.以来气候演变经历了11.0~6.5 ka B.P.、6.5~1.1 ka B.P.和1.1~0 ka B.P.三个阶段。

11.0~6.5 ka B.P., ZYC剖面CIA值、Rb/Sr比值、

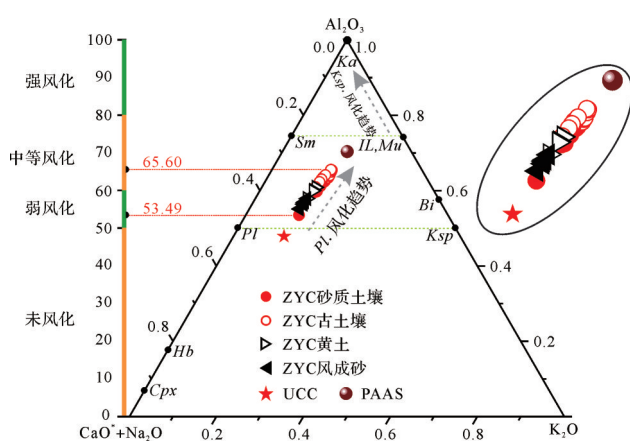


图4 ZYC剖面风成沉积物样品的A-CN-K三元图
(底图引自文献[31])和CIA值

UCC和PAAS^[23]; Ka. 高岭石; Sm. 蒙脱石; IL. 伊利石; Mu. 白云母; Bi. 黑云母; Pl. 斜长石; Ksp. 钾长石; Hb. 角闪石; Cpx. 单斜辉石

Fig.4 Chemical index of alteration (CIA) values and A-CN-K ternary diagram (base map from reference [31]) for aeolian deposit samples from ZYC section

UCC and PAAS^[23]; Ka = kaolinite; Sm = smectite; IL = illite; Mu = muscovite; Bi = biotite; Pl = plagioclase; Ksp = K-feldspar; Hb = hornblende; Cpx = clinopyroxene

磁化率值和TOC含量^[16]为低值,有增高的趋势, L^* 值、中值粒径、 $(CaO+Na_2O+MgO)/Ti_2O$ 比值均为高值,剖面发育风成砂、黄土及部分古土壤(图5m),这些记录揭示该时期青海湖地区风化作用较弱,气候可能相对温暖干旱,与基于烯烃重建的青海湖地区夏季温度显示该时期气温较高(图5j)^[34]和重建的青藏高原东北缘年均降水量显示这一时期降水量较低(图5k)^[35]相印证。在这种气候条件下青海湖湖面较低(图5l)^[11],区内风沙活动较强,风成砂沉积发育(图5a)^[6-7,15-16,36-37]。

6.5~1.1 ka B.P., ZYC剖面CIA值、Rb/Sr比值、磁化率值和TOC含量^[16]都呈高值,且达到峰值,而 L^* 值、中值粒径、 $(CaO+Na_2O+MgO)/Ti_2O$ 比值显著降低,剖面古土壤发育(图5m)。尽管这些指标峰值出现的时间不一致,但是它们均揭示该时期青海湖地区风化作用可能较强,为暖湿期,这与重建的青藏高原东北缘年均降水量显示这一时期降水量较高(图5k)^[35]和基于烯烃重建的青海湖地区夏季温度显示该时期温度相对较高(图5j)^[34]相吻合。在这种暖湿气候条件下,可能造成青海湖湖面上升,出现高湖面,古湖岸堤地貌证据显示全新世最高湖面出现在约5.0 ka B.P.(图5l)^[11]。由于这一暖湿气候持续时间长,冷暖波动少,风沙活动弱,成壤作用较强,区内古土壤发育较厚(图5a)^[6-7,15-16,36-37]。

1.1 ka B.P.至今,剖面发育砂质土壤(图5m), CIA值、Rb/Sr比值、TOC含量^[16]、磁化率值、 $(CaO+Na_2O+MgO)/Ti_2O$ 比值、中值粒径和 L^* 值波动变化,该时期青海湖地区风成砂和古土壤交替出现(图5a)^[6-7,15-16,36-37],重建的该地区夏季温度较高(图5j)^[34],降水量较低(图5k)^[35],表明青海湖地区气候变得干旱。古湖岸堤地貌证据也显示在约1.1 ka B.P.以后青海湖湖面下降(图5l)^[11]。

亚洲季风在很大程度上影响了包括青海湖盆地在内的中国北部沙漠或沙地的演化,其强弱变化可导致气候的干湿变化,从而造成风成砂和古土壤在风成沉积剖面中出现^[7,41]。本次研究结果揭示青海湖地区全新世早期气候相对温暖干旱,可能由于早期太阳辐射增加(图5h)^[38]导致蒸发强度较高,造成青海湖地区有效湿度降低,使得风沙活动加强,风成砂沉积发育(图5a)^[6-7,15-16,36-37],青海湖处于低湖面(图5l)^[11]。而全新世中期,太阳辐射(图5h)^[38]逐渐减弱可能导致蒸发强度逐渐降低,造成青海湖地区有效湿度增加,气候进入湿润期,青海湖地区古土壤沉积大量发育(图5a)^[6-7,15-16,36-37],青海湖湖面在约5.0 ka B.P.达到最高(图5l)^[11]。全新世晚期,太阳辐射变弱,年降雨量减少(图5k)^[35],导致气候变干,发育风成砂沉积(图5a)^[6-7,15-16,36-37]。

综上所述,我们初步认为亚洲季风和太阳辐射的强弱变化可能造成有效湿度的高低变化,从而导致青海湖地区气候干湿交替变化。

5 结论

(1) 青海湖种羊场风成沉积的主量元素相比UCC显著富集CaO,亏损Na₂O,微量元素相比UCC有显著的Nb亏损,而富集V、Cr、Co、Ni、Y、Zr、La。

(2) CIA值和A-CN-K三元图表明种羊场风成沉积经历了弱风化、中等程度的化学风化强度,仍处于斜长石风化早期Ca和Na的去除阶段。CIA值的波动变化反映青海湖地区全新世期间经历了较大的干湿变化。

(3) 种羊场风成沉积物的亮度(L^*)与TOC含量呈高度负相关,可以间接地反映研究区古气候演变过程,而红度(a^*)与磁化率之间不相关,其控制因素有待进一步探究,在重建青海湖地区古气候和环境演变过程时具有局限性,需谨慎使用。

(4) ZYC剖面的多指标分析结果和剖面地层特

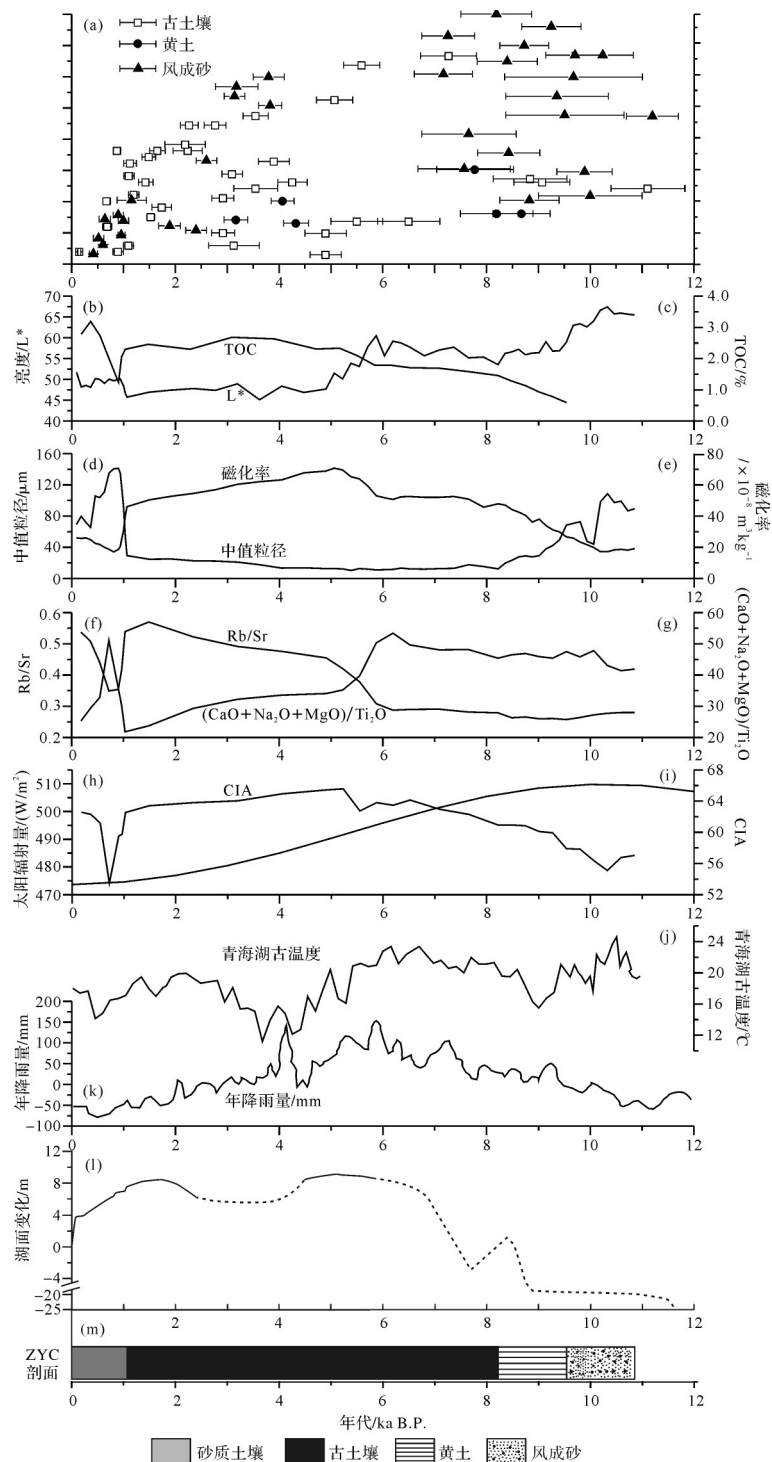


图5 种羊场风成沉积的多指标记录及与其它记录的比较

(a) 青海湖盆地多个风成沉积剖面的 OSL 年代^[6-7,15-16,36-37]; (b) 亮度 (L^*); (c) TOC 含量^[16]; (d) 中值粒径; (e) 磁化率; (f) Rb/Sr; (g) $(CaO+Na_2O+MgO)/Ti_2O$; (h) 30°N 7 月太阳辐射^[38]; (i) CIA; (j) 基于烯烃重建的青海湖夏季温度记录^[34]; (k) 以花粉为基础重建的青藏高原东北缘年均降水量 (PANN) 记录^[35]; (l) 青海湖湖面变化^[11]; (m) 种羊场剖面地层

Fig.5 Multi-proxy records of aeolian deposit samples from ZYC section and comparison with other records:

(a) aeolian deposit OSL ages from the Qinghai Lake area^[6-7,15-16,36-37]; (b) lightness (L^*); (c) total organic carbon (TOC) content^[16]; (d) median size (Md); (e) magnetic susceptibility (MS); (f) Rb/Sr ratio; (g) $(CaO+Na_2O+MgO)/Ti_2O$ ratio; (h) 30°N insolation in July^[38]; (i) CIA; (j) alkenone-based summer temperature record from Lake Qinghai^[34]; (k) pollen-based annual precipitation (PANN) record in northeastern Tibetan Plateau^[35]; (l) Holocene lake level variation of Qinghai Lake^[11]; (m) stratigraphy of the ZYC section

征揭示青海湖地区在 11.0~6.5 ka B.P. 时期,风化作用较弱,气候可能相对温暖干旱,青海湖可能处于低湖面;6.5~1.1 ka B.P. 时期风化作用可能较强,为暖湿期,青海湖为高湖面时期;1.1 ka B.P. 至今,气候变得干旱。亚洲季风和太阳辐射的强弱变化可能造成有效湿度的高低变化,从而导致青海湖地区气候干湿交替变化。

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Geochemical Characteristics of Aeolian Deposits on the Eastern Shore of Qinghai Lake and Their Paleoclimatic Implications since the Holocene

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Abstract: The paleoclimatic evolution of the Qinghai Lake area has long been studied due to the uniqueness of its geographical location. However, the nature of the climate in the area since the last deglaciation, especially in the early Holocene, has been controversial due to the large number of various proxies. In this study, aeolian deposits from the Zhongyangchang (ZYC) section on the eastern shore of Qinghai Lake were analyzed to determine their geochemical properties and associated paleoclimatic implications. The elemental characteristics were combined with magnetic susceptibility (MS), median grain size (Md) and color parameters to reconstruct the evolution of the paleoclimate in the Qinghai Lake area over the past 11 000 years. The results indicate that aeolian deposits in the ZYC section experienced weak to moderate chemical weathering, and that they are still at the early stage of plagioclase weathering (mainly the removal of Ca and Na), as indicated by the chemical index of alteration (CIA) and the Al_2O_3 -($\text{CaO}^* + \text{Na}_2\text{O}$)- K_2O (A-CN-K) ternary diagram. The climate in the study area has alternated greatly between dry and wet, as reflected by the variation of CIA values since the early Holocene. The lightness (L^*) is highly negatively correlated with total organic carbon (TOC) content ($R^2 = 0.71$, $P < 0.01$), indicating changes of regional vegetation coverage and indirectly revealing the evolution of the paleoclimate in the area. The results of multi-proxies together with the stratigraphic distribution characteristics in the ZYC section indicate weak weathering in the Qinghai Lake area from 11.0 to 6.5 ka B.P., and that the climate may have been relatively warm and dry. The high CIA, MS and Rb/Sr ratio, and low $(\text{CaO} + \text{Na}_2\text{O} + \text{MgO})/\text{Ti}_2\text{O}$ ratio, Md and L^* indicate a warm, humid climate from 6.5 to 1.1 ka B.P., consistent with the high lake level indicated by shoreline evidence. Since 1.1 ka B.P., the Qinghai Lake area has become dry. Variation of the intensity of the Asian monsoon and solar radiation may cause the effective humidity to vary, resulting in the alternating wet and dry climate in the Qinghai Lake area.

Key words: Qinghai Lake; Holocene; elemental geochemistry; aeolian deposit; paleoclimate change