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论 文

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青藏高原干旱区湖泊正构烷烃氢同位素记录降水同位素

田茜[1,2], 方小敏[3,4], 王明达[1*]

1. 中国科学院青藏高原研究所环境变化与地表过程重点实验室, 北京 100101;
2. 中国科学院大学, 北京 100049;
3. 中国科学院青藏高原研究所大陆碰撞与高原隆升重点实验室, 北京 100101;
4. 中国科学院青藏高原地球科学卓越创新中心, 北京 100101

* 联系人, E-mail: mdwang@itpcas.ac.cn

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摘要 湖泊和海洋沉积物中正构烷烃氢同位素作为有潜力的古水文和古气候指标已经得到广泛应用, 但是在干旱区由于蒸发强烈而严重影响正构烷烃氢同位素比值, 因此其能否记录降水同位素变化受到质疑. 本研究在青藏高原干旱区采集了21个湖泊表层沉积物(其中20个湖泊年平均降水量<400 mm), 发现其正构烷烃氢同位素(δD_{wax})与年均降水平均氢同位素(δD_{ann})呈现较强相关(r^2=0.84, P<0.001), 其与夏季降水平均氢同位素(δD_{sum})相关性更好(r^2=0.91, P<0.001), 说明降水是控制湖泊沉积物中正构烷烃氢同位素(δD_{wax})变化的主要因素, 在干旱地区正构烷烃氢同位素(δD_{wax})仍然可以反映降水氢同位素(δD_p)信息. 本研究中湖泊表层沉积物正构烷烃和降水之间的氢同位素表观分馏平均值(ε_{wax-p})为−113‰, 较湿润地区偏正, 可能是由于干旱区蒸发强烈引起. 因此沉积正构烷烃氢同位素(δD_{wax})可以作为夏季降水平均氢同位素(δD_p)的替代指标, 记录夏季风强度和古水文变化.

关键词 青藏高原, 干旱地区, 表层沉积物, 降水, 正构烷烃, 氢同位素

降水稳定氢氧同位素是恢复陆地古环境最有效的指标之一[1~4]. 沉积物中叶蜡化合物来源于陆生高等植物, 并且保存于湖泊或海洋沉积物中. 叶蜡化合物氢同位素能够反映降水稳定氢同位素变化, 已经在现代植物[5~9]、表土[10~14]、湖泊表层沉积物[15~22]和海洋表层沉积物[23]及古气候恢复[24~27]中得到了证实. 但是, 上述已有现代研究绝大多数都集中在湿润地区, 如藏东南地区[13]、阿尔卑斯山南部[14]、美国和加拿大东部地区[15]、欧洲西部芬兰等地[16]、非洲喀麦隆地区[20]等. 较为干旱的地区研究十分缺乏, 在美洲地区[17,28,29]和中国黄土高原[30]、青藏高原[7,18,19,31~33]有零星分布. 现在的观点一般认为湿润区叶蜡化合物氢同位素可以记录降水氢同位素[8~11,13~16,20,34]. 干旱区叶蜡化合物氢同位素尽管受到土壤蒸发和植物蒸腾的影响, 部分前人研究认为其仍然能够记录降水氢同位素[7,17,19,28,31,32,35]; 而部分前人研究则认为其不能够记录降水氢同位素[29,30]. 所以, 在干旱区能否利用湖泊沉积物叶蜡化合物氢同位素重建过去降水同位素变化还需要更多的研究去探讨.

青藏高原被称为“第三极”[36]和“亚洲水塔”[37], 平均海拔在4000 m以上, 受多种大气环流相互作用, 如东亚季风、印度季风和西风影响. 但是目前对控制青藏高原气候变化的机制尚不清楚, 因此研究降水同位素的可靠替代指标将有助于获取更多降水同位

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素记录，有助于进一步研究过去季风和西风环流的变化和深入理解青藏高原气候变化的驱动机制．现代青藏高原的气候特点是干旱(年平均降水量<200 mm)和寒冷(年平均温度~0℃)，且在青藏高原上湖泊分布广泛．因此，该地区是研究极干旱区沉积物正构烷烃氢同位素(δD_{wax})气候意义的绝佳场所．

本研究测试了青藏高原21个湖泊表层沉积物的正构烷烃氢同位素(δD_{wax})，绝大多数湖泊位于年均降水量小于400 mm的干旱区．另外，本研究分析了沉积物正构烷烃氢同位素(δD_{wax})和降水氢同位素(δD_p)的相关性，目的在于：(1) 调查干旱地区沉积物正构烷烃氢同位素(δD_{wax})和降水氢同位素(δD_p)之间的关系；(2) 探讨影响沉积物正构烷烃氢同位素(δD_{wax})变化的控制因素；(3) 探讨影响沉积物正构烷烃氢同位素(δD_{wax})和降水氢同位素(δD_p)之间表观分馏值($\varepsilon_{wax\text{-}p}$)的因素．

1 研究材料及方法

1.1 湖泊表层沉积物

本研究中21个湖泊表层沉积物样品于2012~2014年采自青藏高原“东-西”断面(图1；表1)．湖泊海拔从柴达木盆地的2684 m(西台吉乃尔湖)到青藏高原西部的5036 m(松木希错)．近地表大气年均温度(MAT)变化范围为–7.62~6.56℃．年均降水量(MAP)变化范围为41~463 mm，最大年均降水量出现在青藏高原东部(乃日平错)，最小年均降水量出现在柴达木盆地(大苏干湖)[38]．所选湖泊中，有20个湖泊年均降水量小于400 mm．年均相对湿度范围为33%~64%．青藏高原湖泊蒸发非常强烈，几乎所有湖泊年蒸发量都大于2000 mm[39]，在柴达木盆地的湖泊中，如大苏干湖、西台吉乃尔湖和小柴旦湖，年蒸发量更是高达2700~3000 mm[40]．湖泊面积最小为23 km^2(昂古错)，最大为604 km^2(班公错)．水深最小为0.5 m(小柴旦湖)，最大为44 m(戈芒错)．湖水盐度从0.21 g/L (错鄂，淡水湖)到158 g/L (尕斯库勒湖，咸水湖)．湖水pH范围为7.5~9.8．湖泊所在地的覆盖植被有高山草甸、高山草原以及荒漠草原和荒漠灌木[41]．

湖泊表层沉积物是利用Ekman-Birge采泥器在每个湖泊沉积中心采集的，并取用沉积物表层0~0.5 cm的样品，使用Whirl-Pak样品袋收集，存放于冰箱，冷冻保存直到实验室分析之前．

1.2 分析方法

取约5 g样品经冷冻干燥和研磨后，用20 mL二氯甲烷/甲醇混合液(体积比2∶1)超声抽提3次(15 min/次，30℃)．将3次提取液合并，利用高纯氮气将总提取液吹干，利用氨基硅胶柱(LC-NH_2)分离中性和酸性组分．再将中性组分依次用正己烷、二氯甲烷和甲醇洗脱，分别得到正构烷烃、芳烃和极性组分．

正构烷烃的分析测试利用外标法(外标：DRH-008S-R2, AccuStandard)确定化合物种类．化合物含量则通过气相色谱GC-FID(型号：Agilent 7890A)测定．气相色谱条件是：HP-5石英毛细管柱(30 m×0.25 mm×

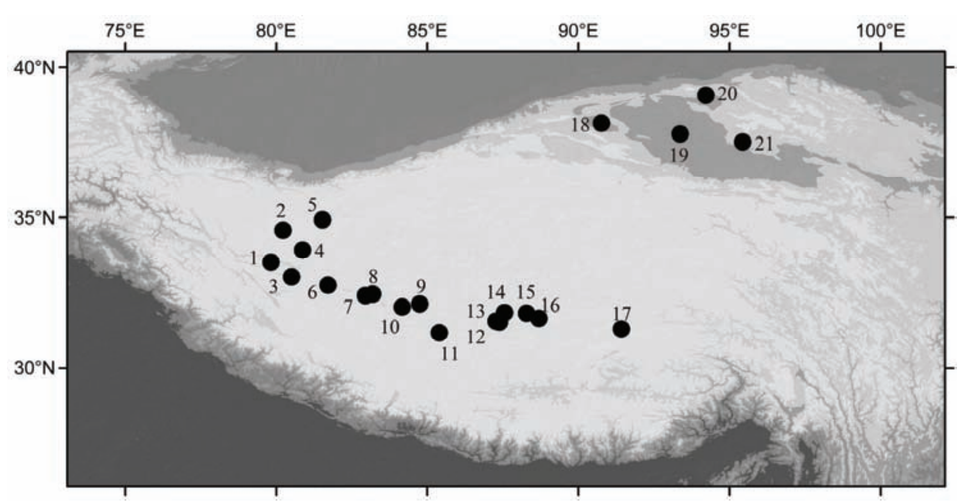

图 1 青藏高原湖泊表层沉积物采样点示意图

Figure 1 Map showing the location of lakes in this study

表 1　本文研究的 21 个青藏高原湖泊地理位置及水化学参数信息[a)]

Table 1　Geographical and limnological data for the 21 Tibetan Plateau lakes

湖泊编号	湖泊名称	纬度	经度	海拔(m)	植被类型	面积(km^2)	水深(m)	盐度(g/L)	pH	MAT (℃)	MAP (mm)	RH (%)	Eva (mm)
1	班公错	33.53°N	79.83°E	4212	高寒草甸	604.0	38.0	0.47	8.73	−1.00	121	35.38	2400~2600
2	松木希错	34.60°N	80.23°E	5036	高寒草甸	24.6	6.5	0.26	8.53	−7.06	142	42.97	2400~2600
3	热邦错	33.04°N	80.51°E	4326	高寒草甸	31.6	0.3	30.05	9.20	0.50	118	35.67	2400~2600
4	结则茶卡	33.94°N	80.88°E	4512	高寒草甸	107.6	6.5	135.00	9.00	−4.17	153	44.41	2400~2600
5	邦达错	34.94°N	81.54°E	4909	高寒草甸	106.5	9.0	35.11	8.50	−7.62	175	51.43	2200~2400
6	阿翁错	32.77°N	81.72°E	4430	高寒草甸	59.0	6.0	27.65	9.20	1.20	167	37.25	2200~2400
7	别若则错	32.42°N	82.96°E	4374	高寒草甸	33.0	2.0	27.38	8.97	1.30	190	37.18	2200~2400
8	达热布错	32.47°N	83.20°E	4410	高山草原	21.0	3.0	1.39	9.35	1.10	186	41.01	2200~2400
9	拉果错	32.05°N	84.17°E	4442	高山草原	91.0	18.0	40.27	8.94	0.70	182	43.07	2200~2400
10	洞错	32.15°N	84.75°E	4362	高山草原	88.0	2.0	46.25	8.82	−3.00	259	47.40	2200~2400
11	昂古错	31.20°N	85.40°E	4679	高山草原	23.0	13.0	1.89	9.10	−2.00	294	44.77	2200~2400
12	戈芒错	31.58°N	87.28°E	4574	高山草原	52.0	44.0	6.35	9.73	−1.00	297	49.29	2200~2400
13	张乃错	31.55°N	87.39°E	4581	高山草原	36.0	16.0	4.06	9.60	0.50	302	58.3	2200~2400
14	达则错	31.87°N	87.56°E	4450	高山草原	245.0	34.0	14.69	9.80	0.95	422	58.07	2200~2400
15	恰规错	31.84°N	88.29°E	4519	高山草原	91.0	26.0	0.22	8.83	−4.00	322	58.76	2000~2200
16	错鄂	31.67°N	88.70°E	4531	高山草原	269.0	27.0	0.21	8.84	1.99	197	57.00	2000~2200
17	乃日平错	31.32°N	91.43°E	4499	高山草原	70.0	8.0	7.96	9.98	0.50	463	64.11	1600~1800
18	尕斯库勒湖	38.13°N	90.77°E	2857	荒漠草甸和灌木	123.0	0.5	158.00	7.50	5.25	111	35.65	2700~3100
19	西台吉乃尔湖	37.78°N	93.37°E	2684	荒漠草甸和灌木	126.0	6.0	35.00	7.70	5.62	90	33.25	2700~3100
20	大苏干湖	39.07°N	94.22°E	2811	荒漠草甸和灌木	120.0	15.0	20.00	8.90	2.00	41	41.47	2700~3100
21	小柴旦湖	37.52°N	95.44°E	3171	荒漠草甸和灌木	71.5	0.5	76.00	8.30	3.52	109	38.43	2700~3100

a) 气象数据提取自中国区域地面气象要素驱动数据集[38]．本文通过对21个湖泊表层沉积物所在点位的近地表气温和当地降水量进行提取，获得2000~2012年气象数据，取12年数据的平均值用于后期分析．蒸发量数据来自于文献[39,40]．MAT，年平均温度；MAP，年平均降水量; RH，年平均相对湿度; Eva，蒸发量

0.25 μm)，进样口温度为320℃，GC温度控制炉升温程序为初始温度80℃，保持2 min，然后以15℃/min速率升温至320℃，保持恒温10 min.

正构烷烃单体氢同位素分析测试在中国科学院地球环境研究所稳定同位素实验室完成．将经过GC分析后的烷烃组分采用气相色谱(Trace GC Ultra)与同位素比值质谱仪(Thermo Fisher Delta V Advantage)联用仪(GC-TCIRMS)测定氢同位素．所用色谱柱为HP-1ms型毛细管柱(60 m×0.32 mm×0.5 μm)．色谱柱进样口温度为290℃，升温程序如下：始温40℃，恒温1 min，以10℃/min升至150℃，再以6℃/min升至310℃，保持20 min．载气为氦气，流速1 mL/min．正构烷烃样品经气相色谱柱分离后进入热解装置，在1450℃下完全裂解为氢气，然后氢气被载气带入同位素比值质谱仪进行氢同位素测定．每6个测试样品加测1个实验室工作标准(C_{21}，C_{25}，C_{27}，C_{29}，C_{31}和C_{33}共6个正构烷烃化合物)，以监控实验过程中氢同位素的重现性和准确性，分析误差<3‰.

2　结果

2.1　大气降水氢同位素(δD_p)

本研究中，所有湖泊所在地对应的降水氢同位素(δD_p)都由在线同位素计算器(Online Isotopes in Precipitation Calculator, OIPC)计算得来[42~44]．该计算器允许根据不同的经纬度和海拔计算现代某地平均每年和每月的氢和氧同位素组成．OIPC使用的数据主要来自国际原子能协会/世界气象组织全球降水同位素，其最大可能地避免了在内插同位素值时出现的局部伪影．OIPC是不断发展进步的，它的数据库在不断扩充，覆盖的区域在不断增加，利用其计算可获得95%置信区间的内插降水同位素值．OIPC建立

了一个计算版本控制系统，其计算版本也在不断地更新．本研究的计算中使用的是OIPC最新版本OIPC 2.2.

所有湖泊对应的年均降水平均氢同位素值(δD_{ann})范围为–78‰~–115‰(图2；表2)，最偏负的δD_{ann}值出现在青藏高原南部，最偏正的δD_{ann}值出现在柴达木盆地．夏季降水平均氢同位素值(7~9月，δD_{sum})范围为–68‰~–126‰(图2；表2)，随纬度变化趋势与δD_{ann}一致.

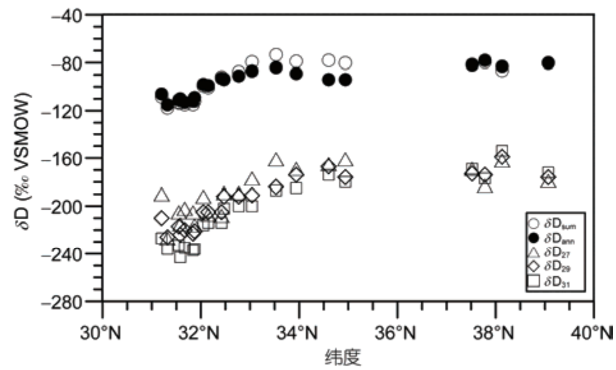

图 2 δD_{sum}, δD_{ann}和C_{27}, C_{29}, C_{31}的δD随纬度的变化. δD_{sum}，夏季(7~9月)降水平均氢同位素；δD_{ann}，年均降水平均氢同位素；δD_{27}，δD_{29}，δD_{31}分别为正构烷烃C_{27}, C_{29}, C_{31}的氢同位素

Figure 2 δD_{sum}, δD_{ann} and δD of C_{27}, C_{29}, C_{31} with latitude change. Hydrogen isotope ratios of summer precipitation (δD_{sum}, July–September), annual precipitation (δD_{ann}), C_{27} *n*-alkane (δD_{27}), C_{29} *n*-alkane (δD_{29}), and C_{31} *n*-alkane (δD_{31}) at the 21 lakes on the Tibetan Plateau

2.2 湖泊表层沉积物正构烷烃氢同位素(δD_{wax})

青藏高原“东-西”断面21个湖泊表层沉积物正构烷烃碳数分布范围为C_{16}~C_{35}(图3)，主要以C_{23}，C_{25}，C_{29}和C_{31}为主峰(图3)，长链正构烷烃具有明显的奇偶优势，表明沉积物长链正构烷烃主要来源于陆生

表 2　大气降水及正构烷烃单体δD值[a)]

Table 2　δD values of atmospheric precipitation and *n*-alkanes

湖泊编号	湖泊名称	δD_{27}	δD_{29}	δD_{31}	δD_{wax}	δD_{sum}	δD_{ann}	$\varepsilon_{27\text{-p}}$	$\varepsilon_{29\text{-p}}$	$\varepsilon_{31\text{-p}}$	$\varepsilon_{wax\text{-p}}$	CPI
1	班公错	–161	–184	–187	–172	–68	–84	–84	–109	–112	–96	4.93
2	松木希错	–165	–167	–174	–169	–69	–94	–78	–81	–88	–83	3.49
3	热邦错	–177	–191	–200	–190	–76	–87	–99	–114	–124	–113	5.42
4	结则茶卡	–169	–174	–185	–177	–73	–89	–88	–93	–105	–97	6.06
5	邦达错	–161	–176	–180	–174	–71	–94	–74	–91	–95	–89	5.73
6	阿翁错	–189	–192	–200	–195	–85	–91	–108	–111	–120	–115	6.73
7	别若则错	–208	–205	–214	–210	–91	–93	–127	–123	–133	–128	7.31
8	达热布错	–189	–192	–202	–194	–93	–94	–105	–108	–119	–110	9.11
9	拉果错	–192	–205	–216	–207	–100	–98	–104	–119	–131	–121	6.26
10	洞错	–207	–205	–214	–210	–102	–99	–120	–118	–128	–123	7.72
11	昂古错	–190	–210	–227	–210	–112	–106	–94	–116	–135	–116	3.41
12	戈芒错	–215	–224	–243	–233	–119	–110	–118	–128	–149	–138	9.81
13	张乃错	–205	–217	–233	–223	–119	–111	–106	–119	–137	–126	8.83
14	达则错	–216	–221	–236	–228	–118	–109	–120	–126	–143	–134	10.32
15	恰规错	–205	–223	–237	–228	–121	–112	–105	–125	–141	–130	10.75
16	错鄂	–202	–220	–235	–225	–122	–113	–100	–121	–138	–126	8.93
17	乃日平错	–227	–226	–236	–232	–126	–115	–127	–125	–137	–132	10.34
18	尕斯库勒湖	–162	–159	–154	–159	–84	–83	–86	–83	–77	–83	3.12
19	西台吉乃尔湖	–183	–174	–177	–180	–78	–78	–114	–104	–107	–111	8.97
20	大苏干湖	–179	–176	–172	–176	–77	–80	–108	–104	–100	–105	4.36
21	小柴旦湖	–169	–173	–169	–171	–80	–82	–95	–99	–95	–96	7.98

a) δD_{27}，δD_{29}，δD_{31}，湖泊表层沉积物正构烷烃C_{27}，C_{29}，C_{31}的δD值；δD_{wax}，δD_{27}，δD_{29}，δD_{31}的加权平均值；δD_{sum}，夏季降水平均值；δD_{ann}，年平均降水平均值；$\varepsilon_{27\text{-p}}$，$\varepsilon_{29\text{-p}}$，$\varepsilon_{31\text{-p}}$，$\delta D_{27}$，$\delta D_{29}$，$\delta D_{31}$和年均降水平均$\delta D$值之间的氢同位素分馏值；CPI，碳优势指数

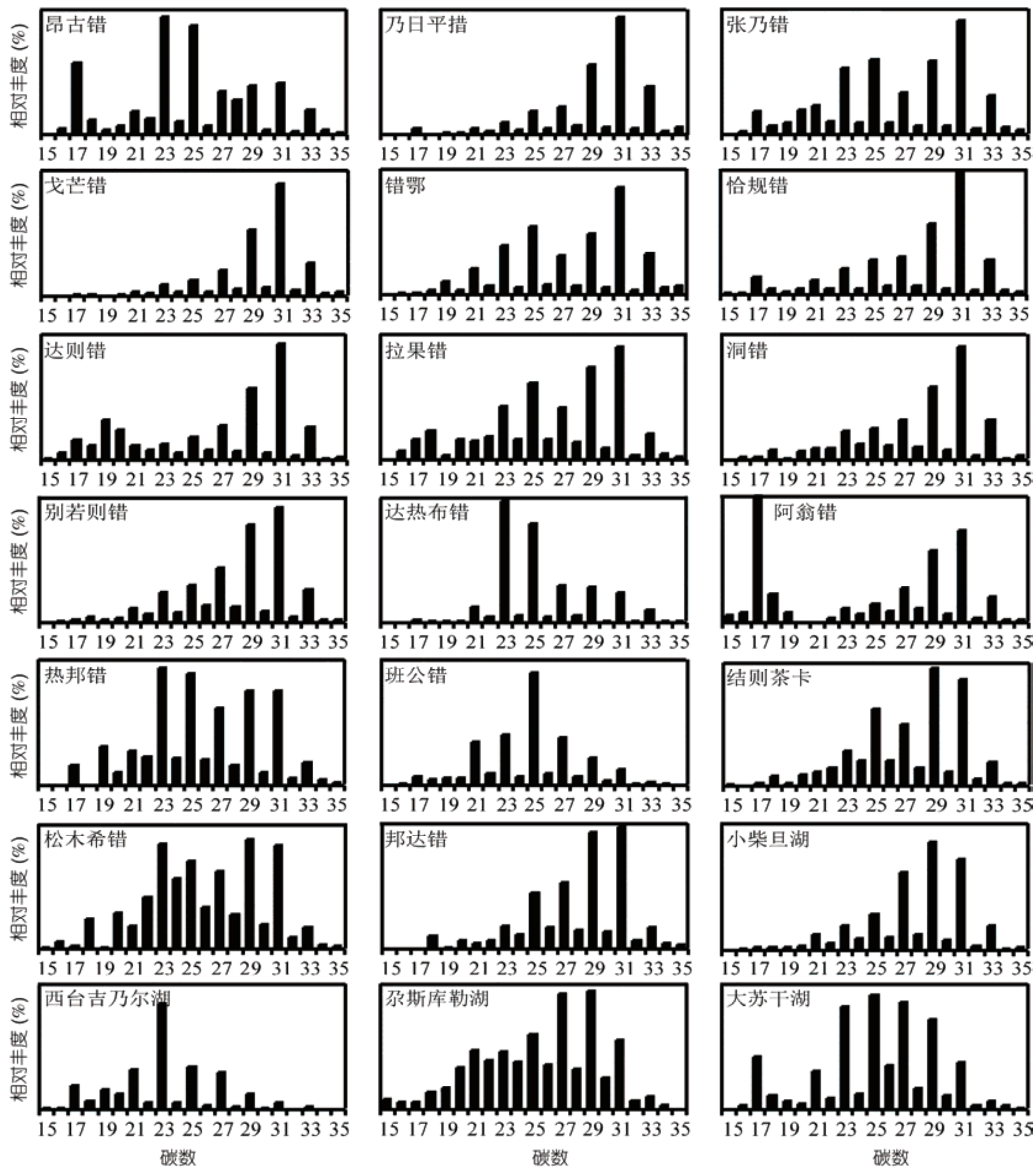

图 3 湖泊表层沉积物正构烷烃分布图

Figure 3 Distribution of *n*-alkanes

高等植物[45,46]. 各个湖泊样品平均碳优势指数(CPI)在3.12~10.75(表2), 其中最低值出现在尕斯库勒湖, 最高值出现在恰规错.

湖泊表层沉积物C_{27}正构烷烃δD值范围为–161‰~–227‰, C_{29}正构烷烃δD值范围为–159‰~–226‰, C_{31}正构烷烃δD值范围为–154‰~–243‰(图2; 表2). C_{27}, C_{29}和C_{31}正构烷烃δD值具有很好的相关性(C_{27}和C_{29}之间r^2=0.83, P<0.001; C_{27}和C_{31}之间r^2=0.78, P<0.001; C_{29}和C_{31}之间r^2=0.98, P<0.001, 表3), 说明它们来源一致.

表 3 正构烷烃δD_{27}, δD_{29}, δD_{31}与降水δD_{sum}, δD_{ann}的相关性

Table 3 Correlation matrix for δD values of C_{27}, C_{29}, C_{31} and precipitation

	δD_{27}	δD_{29}	δD_{31}	δD_{sum}	δD_{ann}
δD_{27}		0.83	0.78	0.78	0.60
δD_{29}			0.98	0.84	0.80
δD_{31}				0.80	0.82

为了检验沉积物正构烷烃和降水δD值之间的关

系，本研究计算了C_{27}，C_{29}和C_{31}正构烷烃δD的加权平均值(δD_{wax}). δD_{wax}可以消除木本和非木本植物来源正构烷烃输入偏差[47~49]，使其能更好地反映区域降水信号. 本研究中，在青藏高原整个“东西断面”上，δD_{wax}值与δD_{ann}值具有显著相关性(r^2=0.84，P<0.001)，与δD_{sum}值得相关性更好(r^2=0.91，P<0.001). 本研究还计算了沉积物叶蜡正构烷烃和降水δD之间的表观分馏值($\varepsilon_{wax\text{-}p}$)，公式如下:

$$\varepsilon_{wax\text{-}p}=1000\times[(\delta D_{wax}+1000)/(\delta D_p+1000)-1]. \qquad (2)$$

在青藏高原整个“东西断面”上，$\varepsilon_{wax\text{-}p}$值范围为−138‰~−83‰，平均值为(−113±17)‰(表1).

3 讨论

3.1 影响青藏高原降水氢同位素(δD_p)的因素

在31°~33°N，随着纬度的增加，δD_{ann}和δD_{sum}值逐渐偏正; 33°~35°N，δD_{ann}和δD_{sum}值无明显变化. 这与全球IAEA/WMO站点降水的δ^{18}O(SMOW)随着纬度的升高而降低的“纬度效应”不同[50]. 但是，在青藏高原现代降水和河水同位素研究中发现δ^{18}O(SMOW)随着纬度的增加而偏正的现象[51~55]，在现代表土叶蜡化合物氢同位素研究中也发现了这种现象[56]. 青藏高原这种异常的氢氧同位素纬向变化可能是由青藏高原特殊的地质地理环境所引起的，即在“季风区”(30°N以南)，受季风影响最大，导致降水和河水δ^{18}O总体贫化; 在“过渡区”(30°~35°N)，受季风影响逐渐减小，在高原面强辐射、西风作用和局地蒸发的高δ^{18}O水汽补充的共同作用下，呈现出较富集的降水和河水δ^{18}O; 在“西风区”(35°N以北)，受西风带或大陆性局地气团影响，呈现出富集的降水和河水δ^{18}O. 青藏高原降水、河水同位素及叶蜡化合物氢同位素纬度变化特征表现的可能是上述3种不同水汽来源空间差异决定.

3.2 青藏高原正构烷烃氢同位素(δD_{wax})记录降水氢同位素(δD_p)的关系

在整个青藏高原“东西断面”上，δD_{wax}与δD_{ann}具有显著相关性(r^2=0.84, n=21, P<0.001)(图4(a)) δD_{wax}与δD_{sum}相关性更好(r^2=0.91, n=21, P<0.001)(图4(b)). 这与欧洲等相对湿润地区前人有关湖泊表层沉积物研究结果一致[16,17,20,28].

来源于陆生高等植物的有机质记录了土壤水同位素信息，而土壤水本质上来源于降水. 因此，湖泊表层沉积物正构烷烃氢同位素值(δD_{wax})与降水氢同位素值(δD_p)相关性很好. 此外，青藏高原降水主要集中于夏季，占全年降水60%~70%[57]，正构烷烃主要在植物生长季节合成[58~60]. 所以，本研究湖泊表层沉积物δD_{wax}与夏季降水δD_{sum}更好.

然而，除了降水同位素，湖泊表层沉积物正构烷烃δD_{wax}还受其他环境和植物生理因素影响，这也可能影响数据相关性. 例如，植被类型是影响沉积物正构烷烃δD_{wax}的重要因素. 而在青藏高原，植被类型

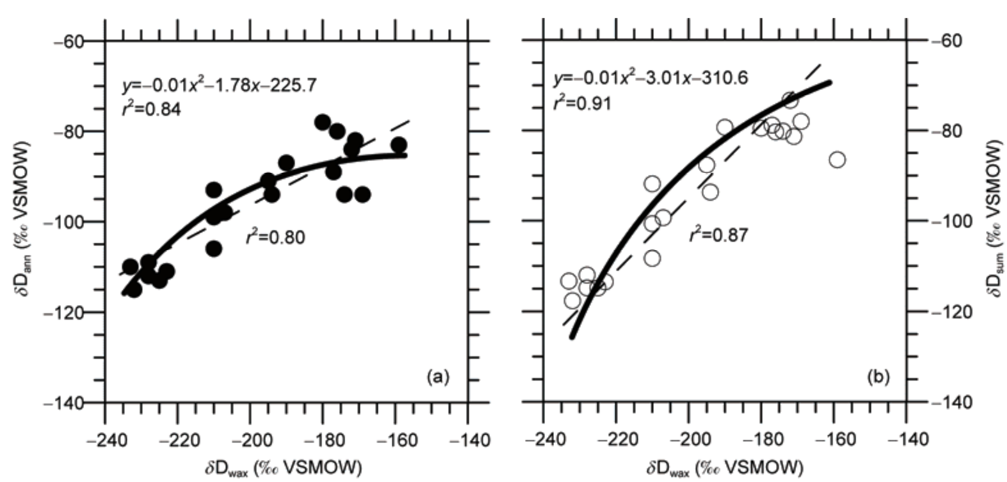

图 4 δD_{wax}与δD_{ann}的关系(a)及δD_{wax}与δD_{sum}的关系(b). 虚线代表线性相关，实线代表二次多项式相关

Figure 4 Correlation of δD_{wax} values with δD_{ann} values (a), and δD_{sum} values (b). Dash line represents the linear regression; solid line represents the quadratic polynomial correlation

随着海拔变化会发生改变[41]. 在海拔相对较低的大苏干湖(2811 m), 植被类型主要为灌木和草本. 在海拔相对较高的达则错(4450 m), 植被类型主要为草本. 植物蒸腾和土壤蒸发也是影响沉积物正构烷烃δD_{wax}的重要因素[58]. 青藏高原和柴达木盆地降水量都非常缺乏、蒸发十分严重. 本研究中, 大部分湖泊年均降水量低于400 mm. 位于柴达木盆地的尕斯库勒湖降水量仅为17.6 mm, 蒸发量却大于3000 mm[61]. 土壤水分的蒸发作用和叶片表层水分的蒸发蒸腾作用强烈使得正构烷烃的氢源更富集氘同位素.

3.3 沉积物正构烷烃氢同位素(δD_{wax})与降水氢同位素(δD_p)之间的表观分馏值($\varepsilon_{wax\text{-}p}$)

氢同位素的表观分馏ε是指正构烷烃单分子δD_{wax}与源水δD_p的关系, 若表观分馏稳定, 则正构烷烃的δD_{wax}反映了源水δD_p的变化, 从而反映影响源水变化的气候要素. 本研究中, $\varepsilon_{27\text{-}p}$, $\varepsilon_{29\text{-}p}$和$\varepsilon_{31\text{-}p}$的范围分别为–127‰~–74‰(平均值: –103‰, SD=15), –81‰~–128‰(平均值: –110‰, SD=14), 和–149‰~–77‰(平均值: –120‰, SD=20)(表1). $\varepsilon_{wax\text{-}p}$的范围为–138‰~–83‰(平均值: –113 ‰, SD=17)(表1).

将本研究$\varepsilon_{wax\text{-}p}$与世界其他湿润地区, 如欧洲西部[16], 美洲[17,28], 非洲中部[20]和青藏高原东南部[19] $\varepsilon_{wax\text{-}p}$值及青藏高原干旱区[18,22] $\varepsilon_{wax\text{-}p}$值对比, 发现湿润区$\varepsilon_{wax\text{-}p}$较干旱区更偏负(图5). 本文认为原因主要是因为干旱区土壤蒸发和植物蒸腾作用更强烈(图6). 本研究中湖泊所在地的平均降水量和蒸发量分别为207和2343 mm(表1). 而在相对湿润的地区, 如青藏高原东南部, 年降水量和年蒸发量分别为1298和795 mm[19]. 干旱区蒸发量远远大于湿润区而降水量远远小于湿润区, 这使得正构烷烃δD_{wax}更富集重同位素, 从而使降水与正构烷烃δD_{wax}之间表观分馏绝对值减小.

3.4 古气候重建的启示

以上研究表明, 正构烷烃氢同位素(δD_{wax})可以记录降水氢同位素(δD_p)信息, 尤其是夏季降水氢同位素(δD_p)信息. 在青藏高原上, 夏季降水水汽是由季风和西风输送[62]. 因此, 正构烷烃氢同位素(δD_{wax})可以真实记录降水同位素信息, 并应用于青藏高原古气候重建[63,64].

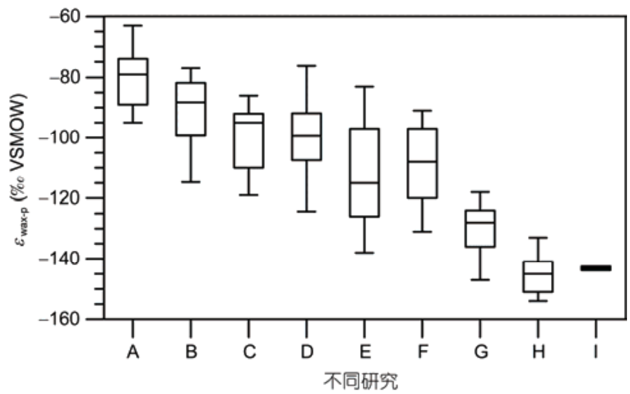

图 5 本研究$\varepsilon_{wax\text{-}p}$与世界其他地区$\varepsilon_{wax\text{-}p}$的对比. 全球不同地区氢同位素表观分馏值. A, 青藏高原, 平均降水量为266 mm[18]; B, 青藏高原, 平均降水量为 370 mm [19]; C, 青藏高原, 平均降水量为 332 mm[22]; D, 美国西南断面, 平均降水量为486 mm[17]; E, 本研究, 平均降水量为207 mm; F, 美国南北断面, 平均降水量为486 mm[28]; G, 欧洲南北断面, 平均降水量为705 mm[16]; H, 青藏高原, 平均降水量为1410 mm[19]; I, 非洲中部南北断面, 平均降水量为2796 mm[20]

Figure 5 Comparison of $\varepsilon_{wax\text{-}p}$ values in this study with $\varepsilon_{wax\text{-}p}$ values in the rest of the world. A, Tibetan Plateau, precipitation is 266 mm[18]; B, Tibetan Plateau, precipitation is 370 mm[19]; C, Tibetan Plateau, precipitation is 332 mm[22]; D, S-W transect of USA, precipitation is 486 mm[17]; E, this study, precipitation is 207 mm; F, N-S transect of USA, precipitation is 486 mm[28]; G, N-S transect of European, precipitation is 705 mm[16]; H, Tibetan Plateau, precipitation is 1410 mm[19]; I, N-S transect of Central Africa, precipitation is 2796 mm[20]

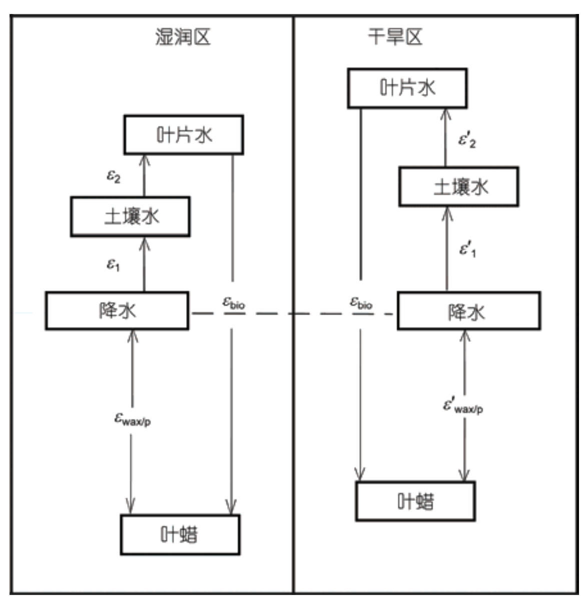

图 6 干旱区和湿润区从降水到土壤水、叶片水和叶蜡δD对比(修改自文献[17]). 在青藏高原, 由于蒸发强烈、降水稀少, 土壤水和叶片水比湿润区更富集重同位素

Figure 6 Hydrogen isotope variation from precipitation, to soil water, to leaf water, to leaf waxes in arid regions and humid regions (modified from Ref. [17]). In arid regions, such as the Tibetan Plateau, the soil water and leaf water are more strongly enriched in deuterium than those in humid regions

4 结论

通过对青藏高原“东-西”断面21个湖泊表层沉积物叶蜡正构烷烃氢同位素的系统研究，得到以下结论：湖泊表层沉积物正构烷烃氢同位素(δD_{wax})与年均降水平均氢同位素(δD_{ann})呈现较强相关(r^2=0.84)，其与夏季降水氢同位素(δD_{sum})相关性更好(r^2=0.91). 在青藏高原“东-西”断面上，ε_{wax-p}范围为–83‰~ –138‰(平均值：113‰，SD=17)，较为恒定. 说明在青藏高原干旱区沉积物正构烷烃δD_{wax}可以记录降水同位素信号，尤其是夏季降水同位素信号.

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Summary for “青藏高原干旱区湖泊正构烷烃氢同位素记录降水同位素”

Sedimentary *n*-alkanes record of precipitation D/H ratios in arid regions of the Tibetan Plateau

TIAN Qian[1,2], FANG XiaoMin[3,4] & WANG MingDa[1*]

[1] *Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China;*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China;*
[3] *Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China;*
[4] *Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China*
* Corresponding author, E-mail: mdwang@itpcas.ac.cn

The hydrogen isotope ratios of sedimentary leaf waxes have been investigated in various environments and are considered as a promising proxy for paleohydrological and paleoclimatic reconstruction. However, there is a growing concern regarding whether or not sedimentary leaf waxes can be used as an environmental proxy in extremely arid regions, where intensified evaporation strongly enriches the deuterium both in water and in leaf waxes. Here we present a record of the *n*-alkane D/H ratios of surface sediments from 21 lakes. The data were collected from 2012–2014. The *n*-alkanes extracted from lake surface sediments range from nC_{16} to nC_{35}, with the most abundant compounds being nC_{23}, nC_{25}, nC_{29} and nC_{31}. In addition, there is an evident odd-over-even preference for long-chain *n*-alkanes, with carbon preference index (CPI) values varying between 3.41 and 10.75, suggesting that the long-chain sedimentary *n*-alkanes mainly originated from terrestrial plants in arid regions on the Tibetan Plateau. The D/H ratios of the precipitation (δD_p) at all the lakes in this study were calculated using the Online Isotopes in Precipitation Calculator. The OIPC calculates precipitation isotope ratios at a given site by combining an empirical model for isotopic trends related to latitude and altitude with detrended interpolation based on the isotope data from stations in the Global Network of Isotopes in Precipitation. The mean annual hydrogen isotopes ratios of precipitation (δD_{ann}) at the lakes in this study vary from −78‰ to −115‰, with lower precipitation δD values occurring in the southern TP and higher values in the northern TP and the Qaidam Basin. The δD values for summer precipitation (July–September, δD_{sum}) range from −68‰ to −126‰, with a similar range of variation for δD_{ann}. The sedimentary *n*-alkane D/H ratios are strongly correlated with the D/H ratios of annual precipitation (r^2=0.84) and summer precipitation (r^2=0.91), suggesting that the hydrogen isotope signal in sedimentary *n*–alkanes is mainly derived from precipitation, and that the *n*-alkane D/H ratios may reflect the D/H ratios of precipitation in arid regions on the Tibetan Plateau. Water is the ultimate source of hydrogen in plant tissues, and organic matter derived from terrestrial plants should record the isotopic ratio of soil water, which is ultimately recharged by precipitation. The δD values of *n*-alkanes in lake surface sediments could thus be expected to be correlated with the δD values of precipitation, on a large spatial scale. Furthermore, precipitation on the Tibetan Plateau mainly occurs from July to September, which accounts for ~70% during the year, and the *n*-alkanes of leaf wax are synthesized during the plant growing season. Therefore, it is unsurprising that the best correlation between D/H ratios of sedimentary leaf wax and precipitation occurs in the summer months. The apparent hydrogen isotopic fractionation between sedimentary *n*-alkanes and precipitation averages −113‰, evidently smaller than that in relatively humid regions. A possible reason for the smaller apparent fractionation might be spatial differences in soil evaporation and plant transpiration. Mean annual precipitation amount and mean annual evaporation at the studied lakes is 207 and 2343 mm, respectively. However, in the humid areas, such as the southeastern TP, the mean annual precipitation amount and mean annual evaporation are 1298 and 795 mm, respectively. Due to the strong evaporation in arid regions, the δD values of soil water and plant water are more isotopically-enriched relative to precipitation than those in humid regions. Overall, our results demonstrate that sedimentary *n*-alkanes can be used as a proxy indicator of variations in the isotopic composition of summer precipitation, in order to document past changes in summer monsoon intensity and hydrology.

Tibetan Plateau, arid regions, surface sediments, precipitation, *n*-alkane, hydrogen isotopes

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