



中国同位素水文学论坛



i
c water

开启水循环动力学研究新征程—— 我国同位素水文学研究进展评述

庞忠和

中国科学院地质与地球物理研究所

中国科学院地热研究中心（筹）

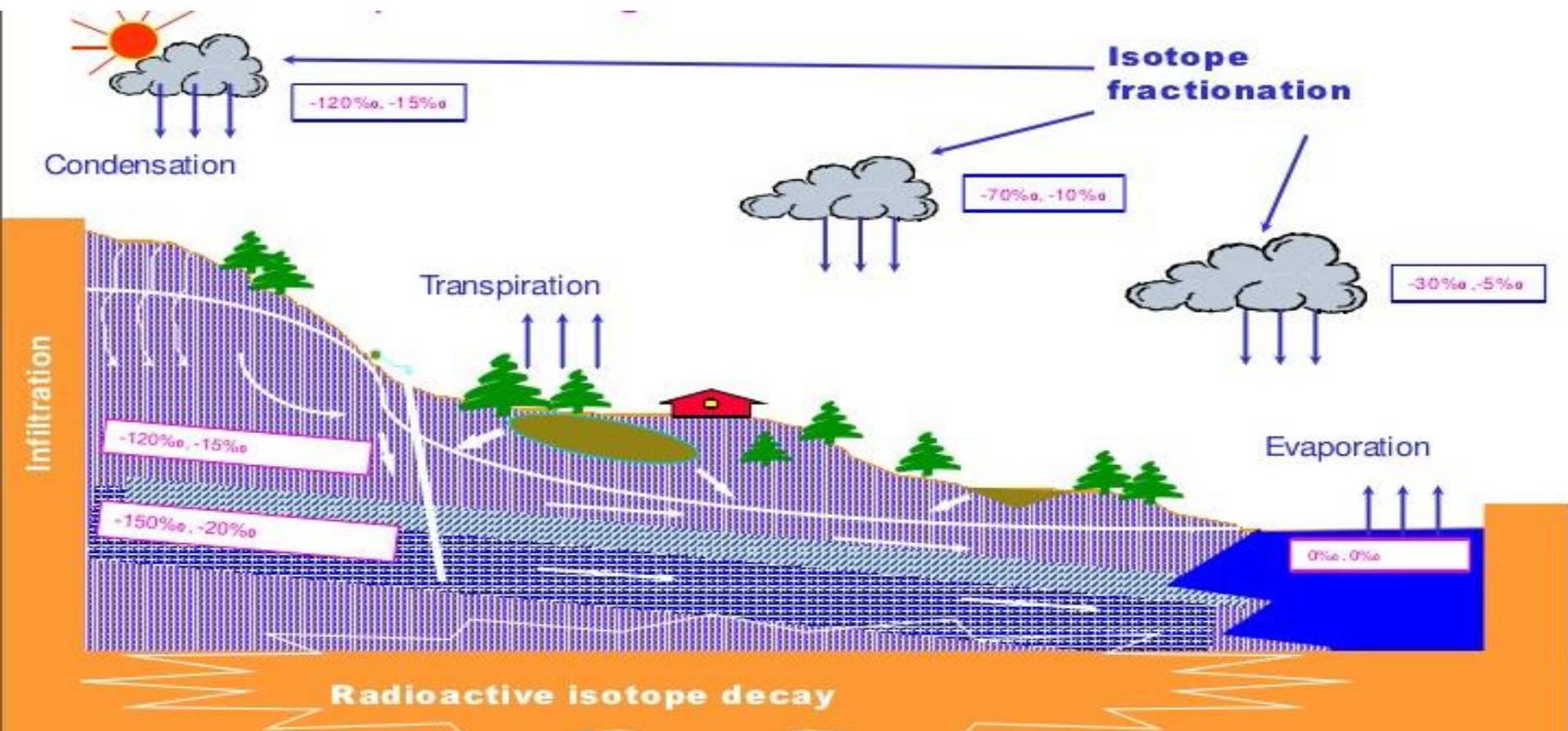
z.pang@mail.iggcas.ac.cn



提纲

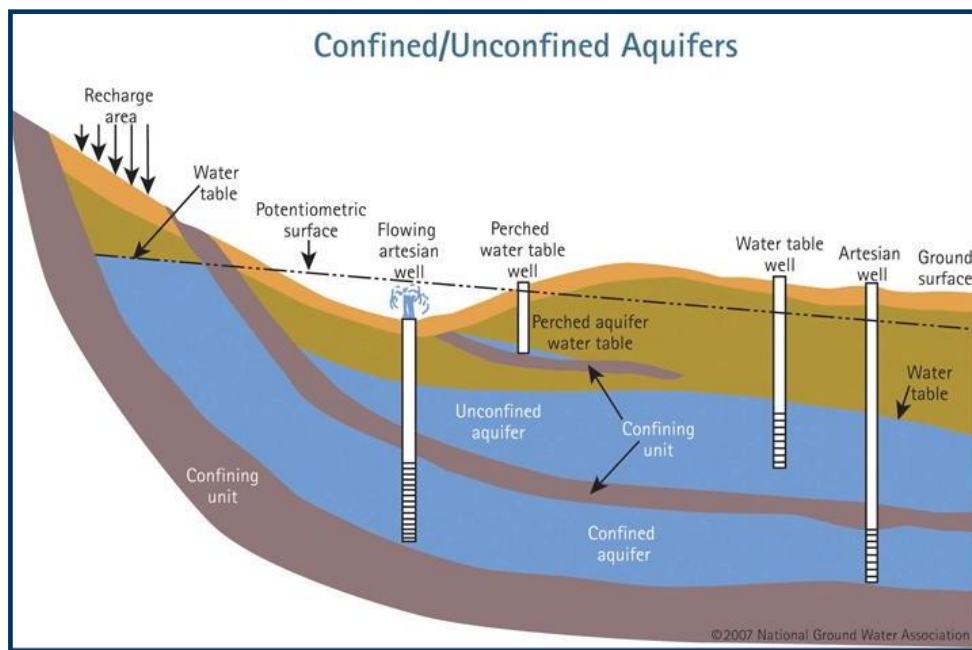
- 引言：地球系统水循环
- 水循环界面过程的识别
- 水循环的新驱动力
- 结语：机遇与挑战

地球系统水循环与同位素变化

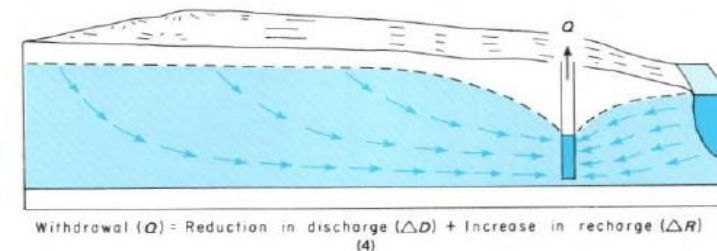
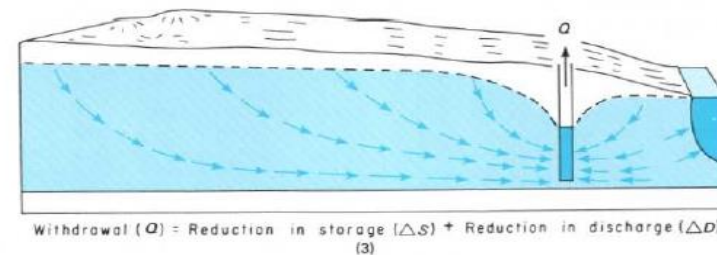
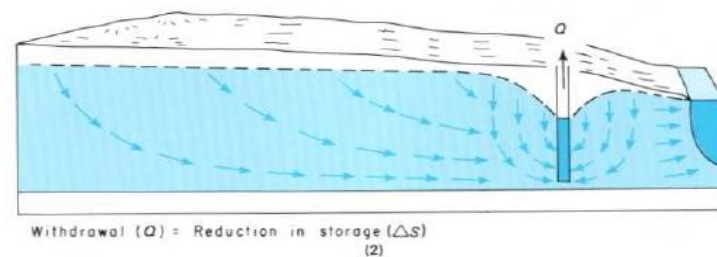
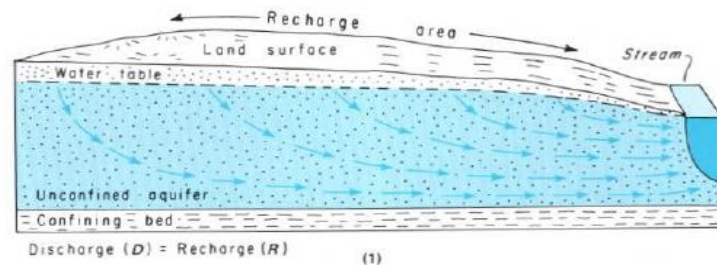


(Pang et al., 2017)

地下水循环系统的结构



(National Ground Water Association, 2007)



(USGS, 1983)

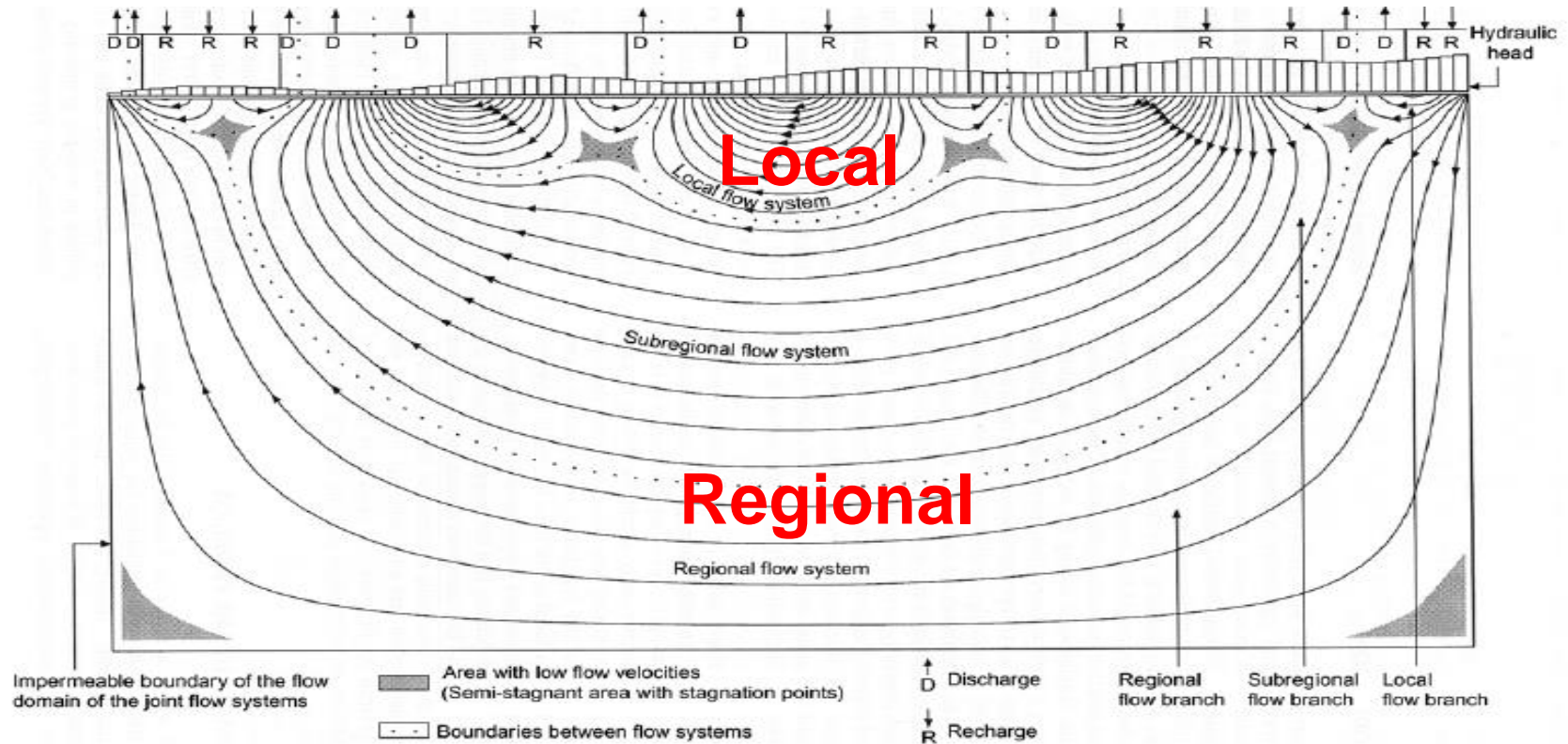


Figure 1 Example of Toth's hierarchically nested groundwater flow systems (after Engelen and Kloosterman, 1996).

- 从Darcy (1856) 砂柱实验, 水位 (头) 差是主要驱动力;
- 到Toth (1965) 地下水盆地重力分级流动模型, 地形高差是主要驱动力, 都是系统内部过程;
- 那么, 系统的界面上发生着什么?



提纲

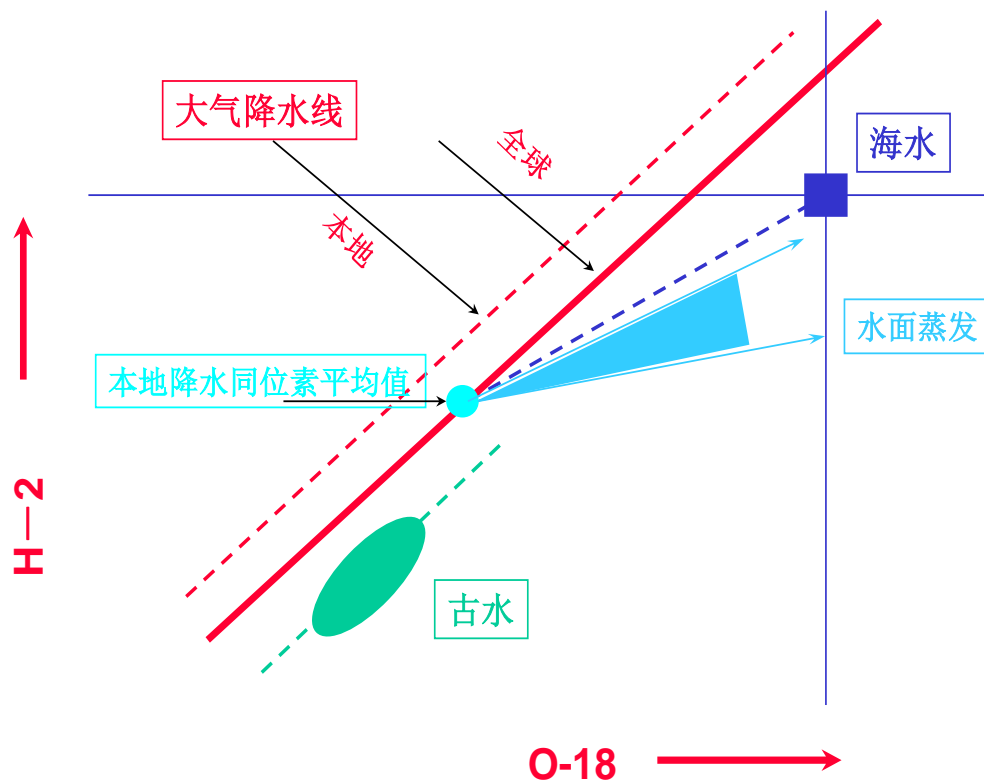
- 引言：地球系统水循环
- **水循环界面过程的识别**
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同位素水文学：跨越地球水系统边界的水文学！

大气降水线：我们从这里起步——同位素水文学第一定律；

还有一条蒸发线！

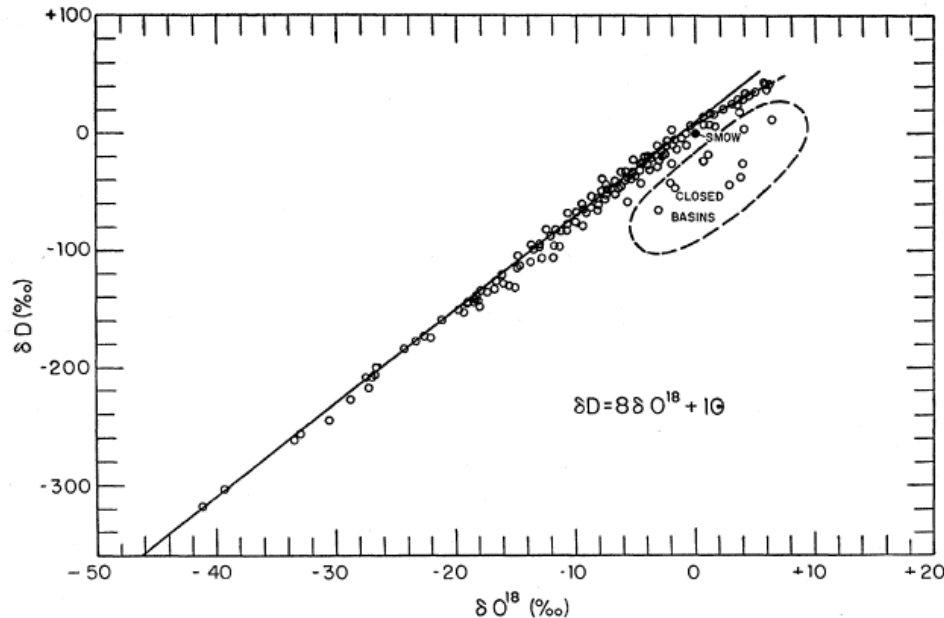
其它过程我们曾经认识的并不多！



(Craig, 1961, Science)



$$\text{GMWL: } \delta^2\text{H} = 8\delta^{18}\text{O} + 10\text{‰}$$

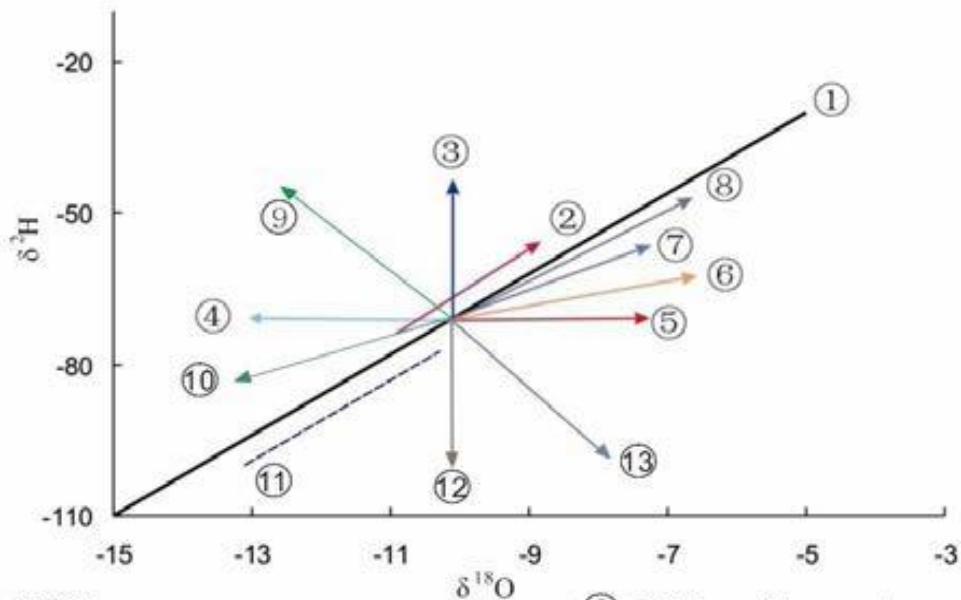


Deuterium and oxygen-18 variations in rivers, lakes, rain, and snow, expressed as per millage enrichments relative to "standard mean ocean water" (SMOW). Points which fit the dashed line at upper end of the curve are rivers and lakes from East Africa.

水稳定同位素十三线图：今天我们了解了这么多！

- 水文过程
- 水热过程
- 水岩作用过程
- 水岩气作用过程

满满当当十三个过程！水循环“原子基因”已经被我们解码？！

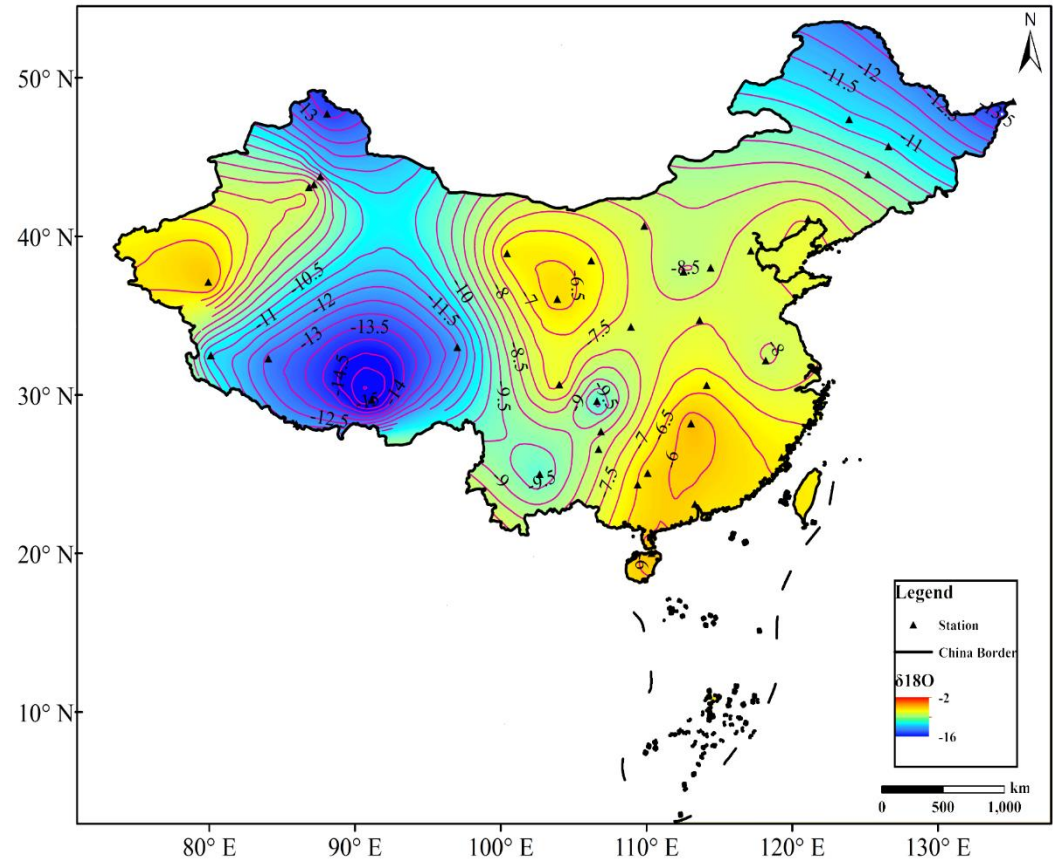


- | | |
|---|---|
| ① GMWL | ⑧ Mixing with seawater |
| ② Moisture recycling | ⑨ Isotopic exchange with silicate mineral |
| ③ Isotopic exchange with H ₂ S | ⑩ Condensation process of moisture |
| ④ Isotopic exchange with CO ₂ | ⑪ Paleo meteoric water |
| ⑤ Water-rock interaction in geothermal system | ⑫ Isotopic exchange with hydrocarbon |
| ⑥ Mixing with andesitic water | ⑬ Isotopic exchange with clay mineral |
| ⑦ Evaporation process | |

(Pang et al.,2017)

中国大气降水同位素分布图

中国大气降水同位素观测工作，自上个世纪80年代以来，陆续由不同单位开展观测工作，积累了30余年的时间系列。目前，按水汽源分出7个大区，均有可资应用的区域雨水线。



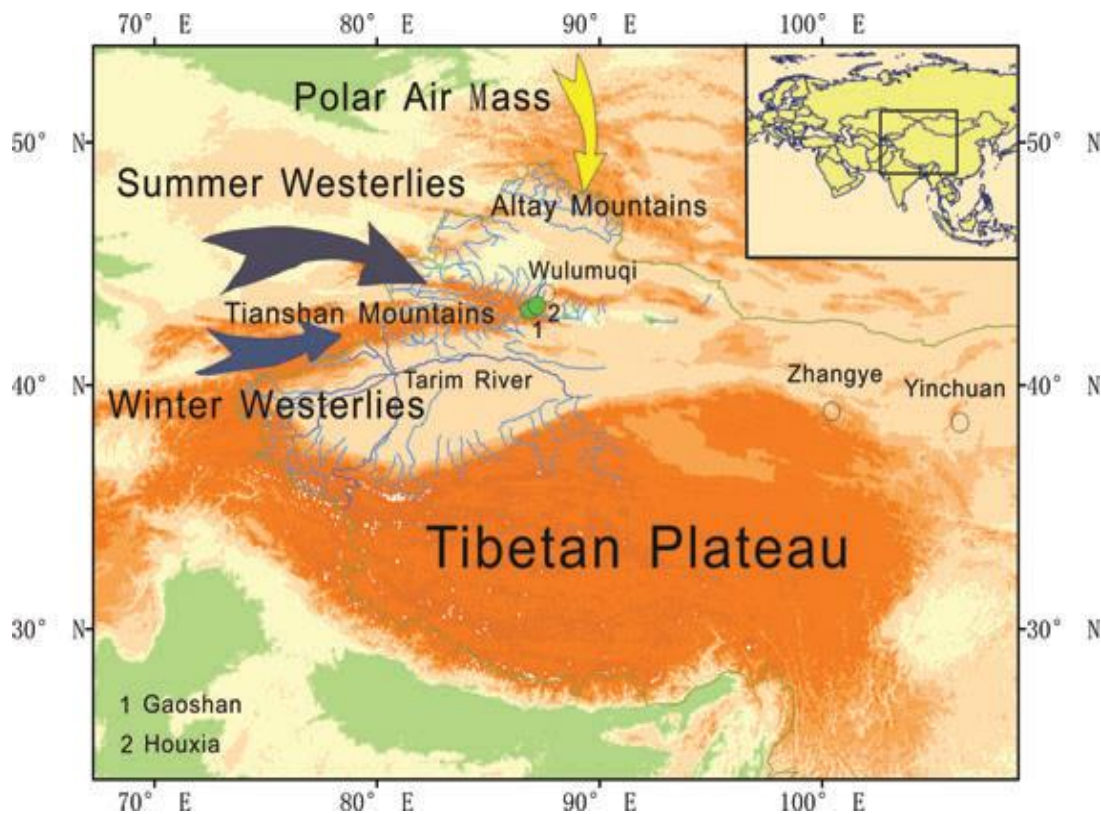
(Kong & Pang et al., 2020)

重点区域更加精细
的水同位素观测网
络:

从月均采样;

到日均采样;

再到逐次采样!

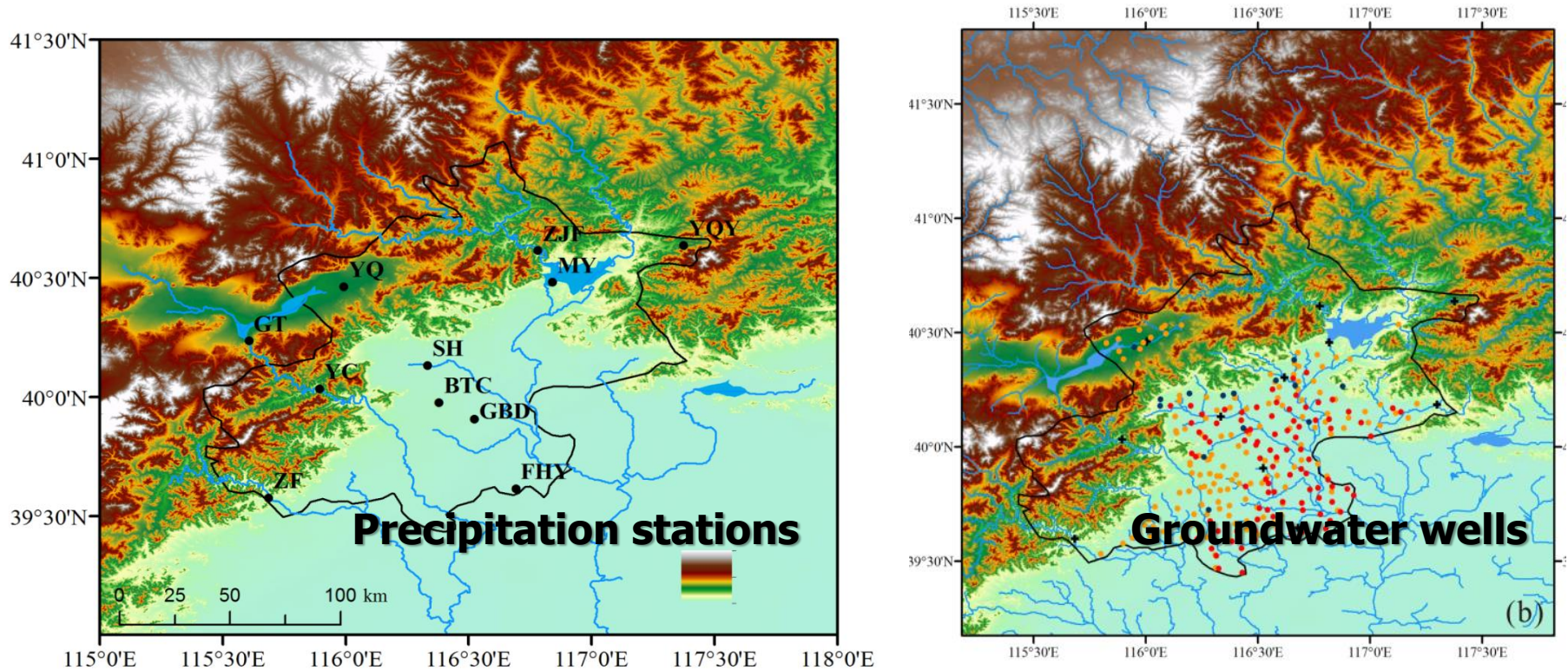


新疆降水同位素与水汽源分布

$$\text{LMWL: } \delta^2\text{H} = 7.05\delta^{18}\text{O} + 0.60\text{‰}$$

(Pang Z, et al.,2011)

北京地区水同位素观测网: Beijing Network of Isotopes in Waters (BNIW)



Precipitation: event-based, in operation since 2014

Groundwater: sampling in the wet season (September) and in the dry season (April)

(Li, Pang, et al., 2018 JGR)



ZJF station



MY Station

The amount of precipitation (P ,mm), temperature (T , $^{\circ}$ C), relative humidity (RH , %), and so on are measured at each observation station.



Automatic temperature and humidity recorder



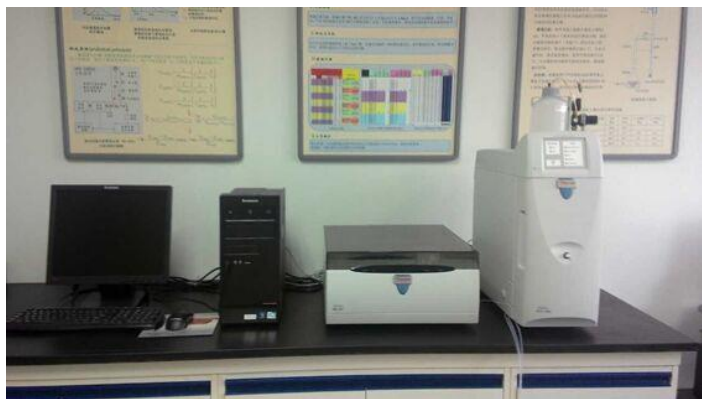
Artificial rain gauge



Microclimate instrument

稳定同位素激光光谱测试技术

水化学分析



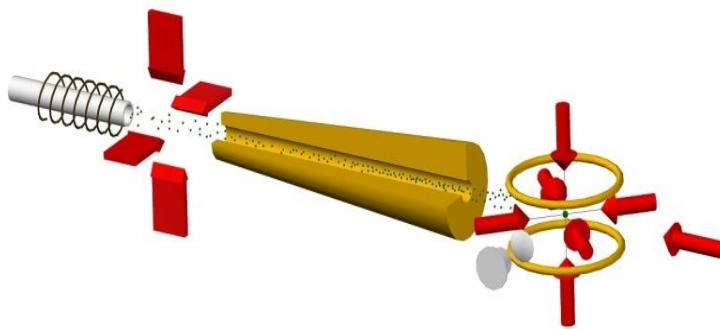
氢氧同位素



硫同位素



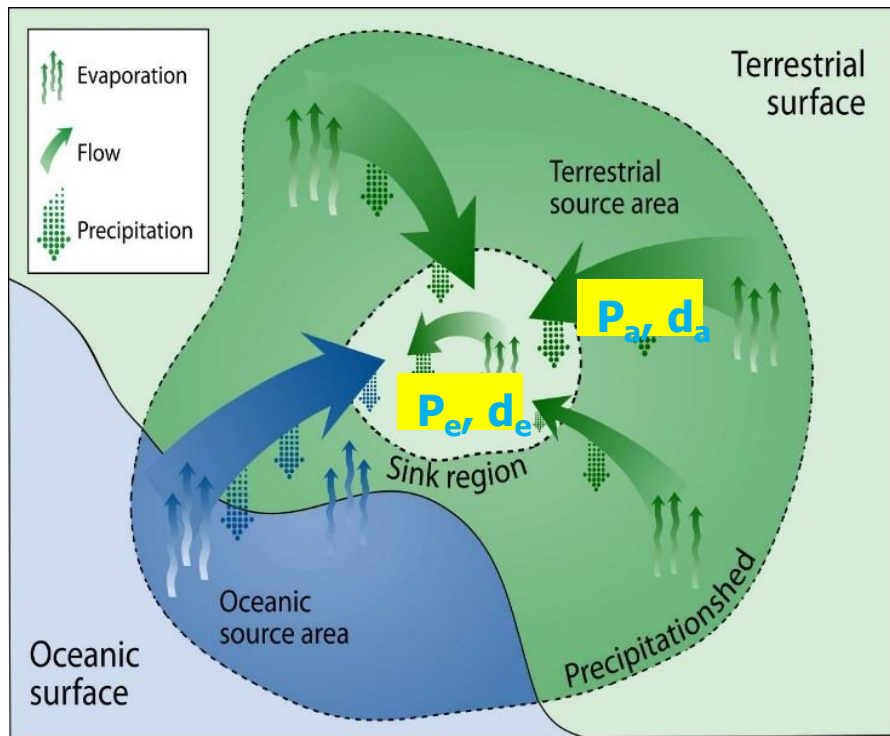
锝同位素



惰性气体 ^{81}Kr

瑞利模型、水汽再循环模型:

水同位素观测数据定量化分析与大气环流观测相结合!
氘盈余得到更多应用!



P: precipitation

d: d-excess

P_e: precipitation from local moisture

d_e: d-excess of P_e

P_a: precipitation from external moisture

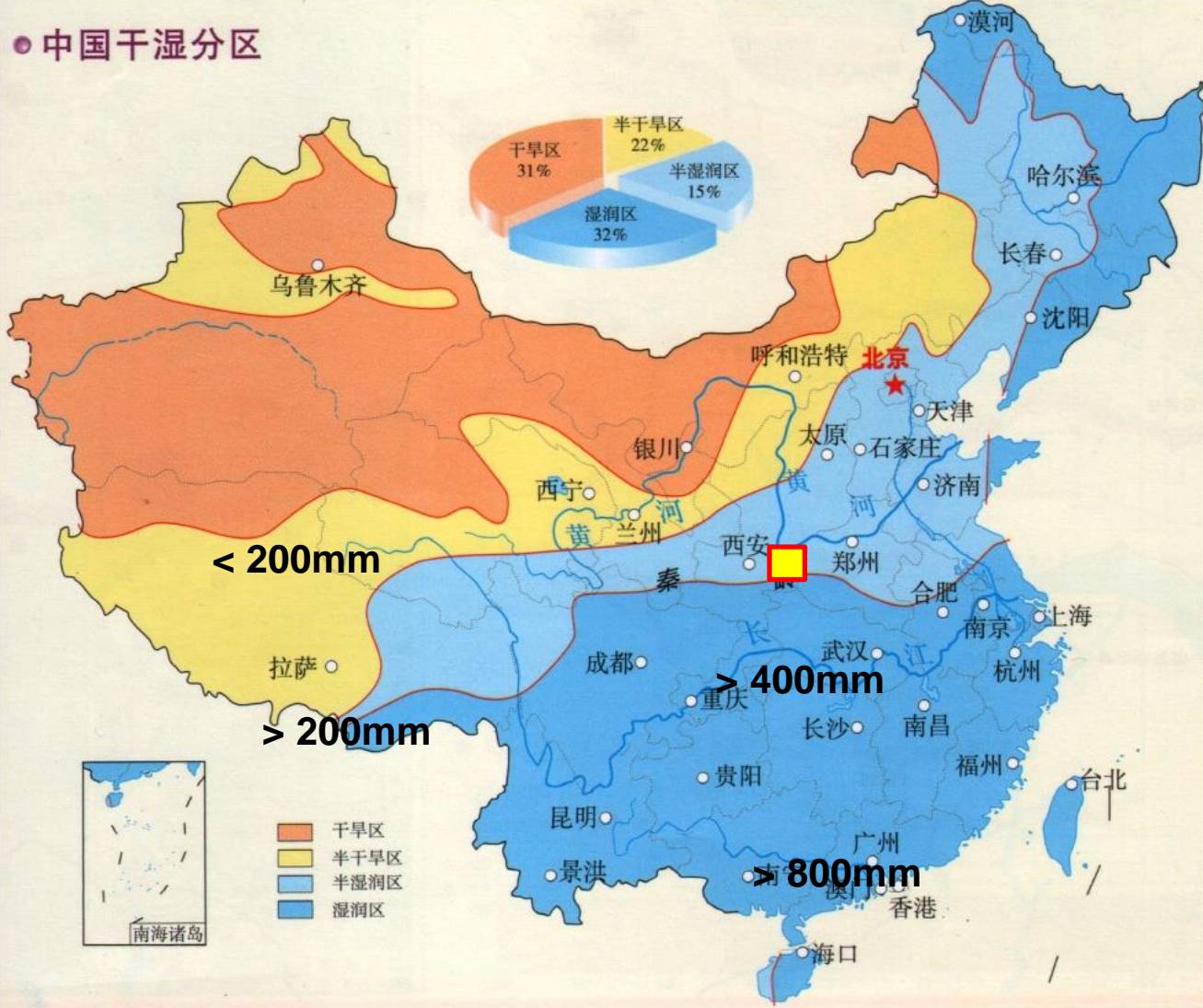
d_a: d-excess of P_a

$$P = P_e + P_a$$

$$d = d_e f_e + d_a (1 - f_e)$$

(Kong & Pang, 2012, JH)

● 中国干湿分区



How does the groundwater circulate?

Map of dry and wet areas in China



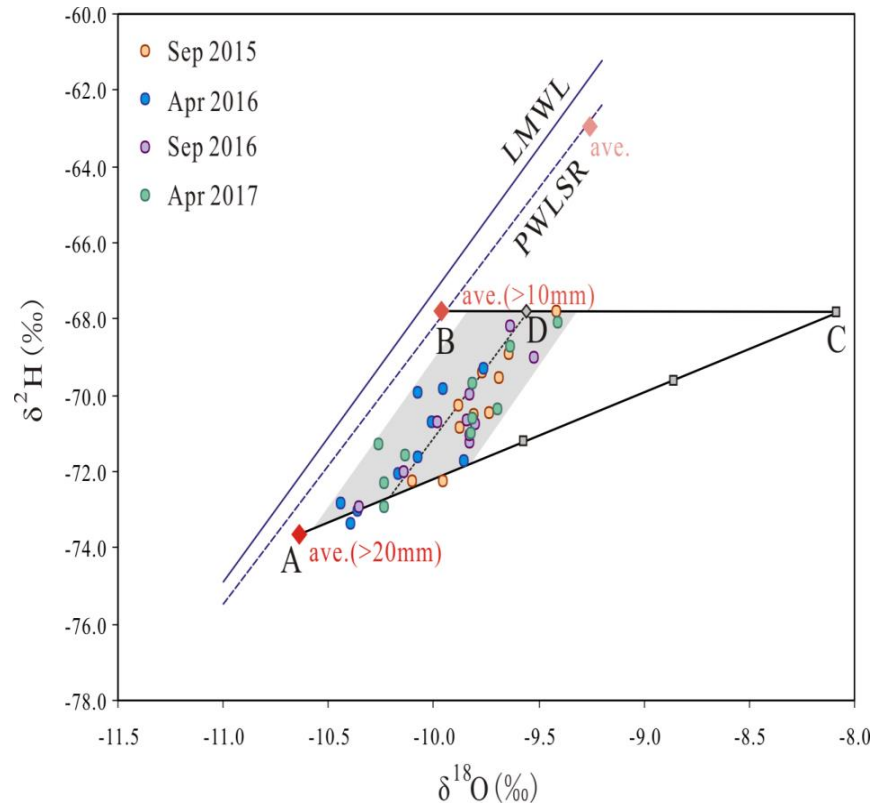
中国主要区域地下水盆地



地下水补给研究的新进展:

- 1) 北京的地下水补给对于大气降水的选择性!
- 2) 西南地区降水与地下水的同位素不对应性!

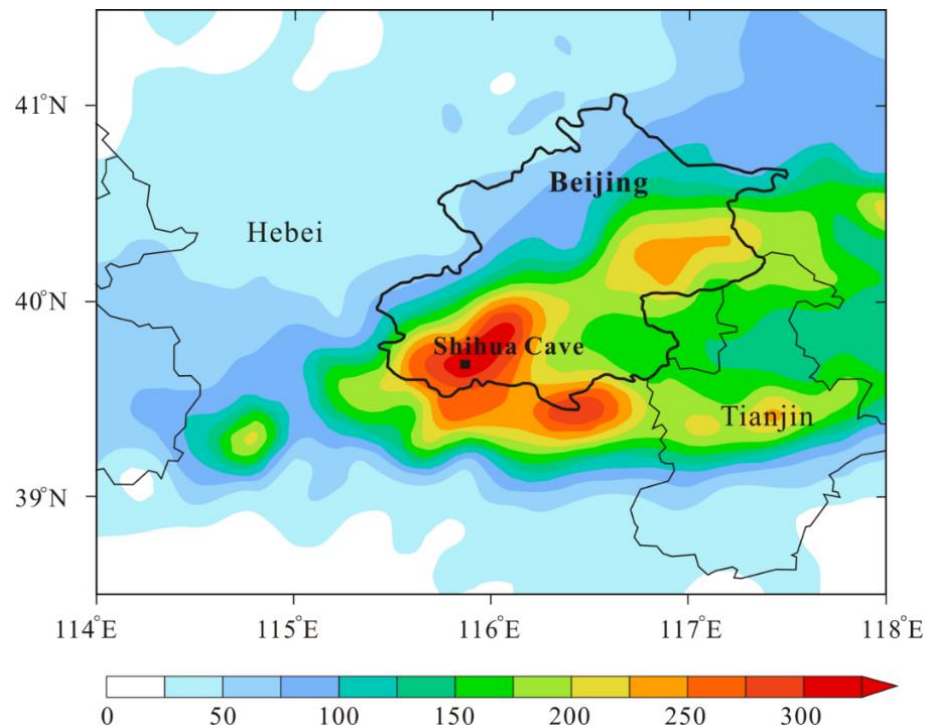
$\delta^{18}\text{O}$ - $\delta^2\text{H}$ relationships for groundwater in Beijing



(Li, Pang, et al., 2018 JGR; Kong et al., 2019, JGR)

极端气候事件成因研究:

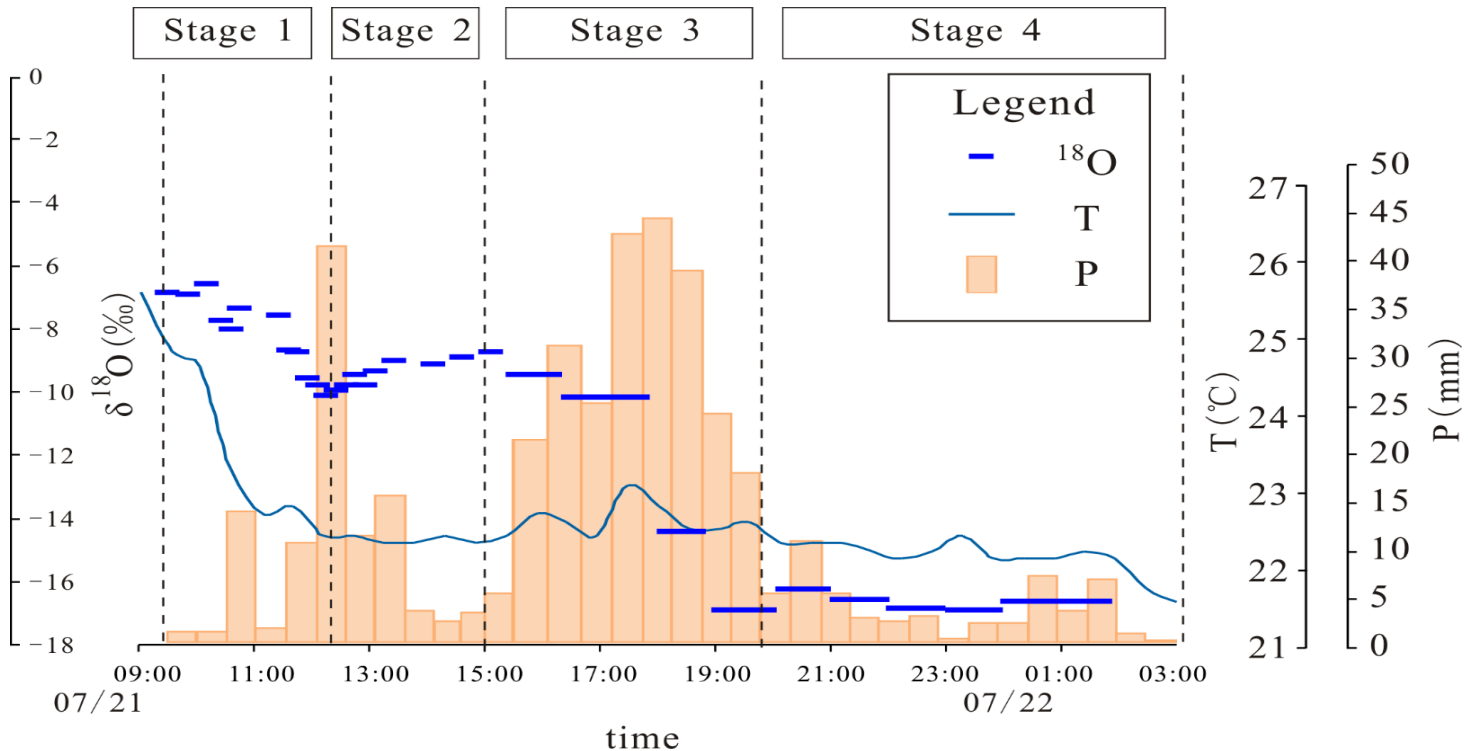
3) 北京的7.21特强降水事件



**Distribution of rainfall amount
in 24 hours (21 -22 July)**

(Li, Pang, et al., 2015)

^{18}O variations in the rainfall

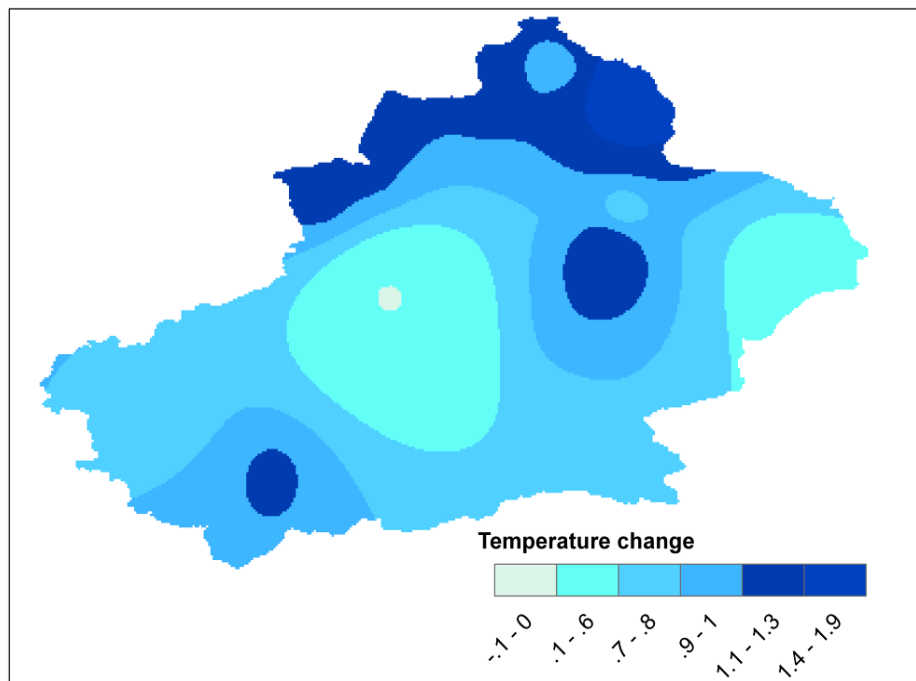


Three rainfall processes are indicated :

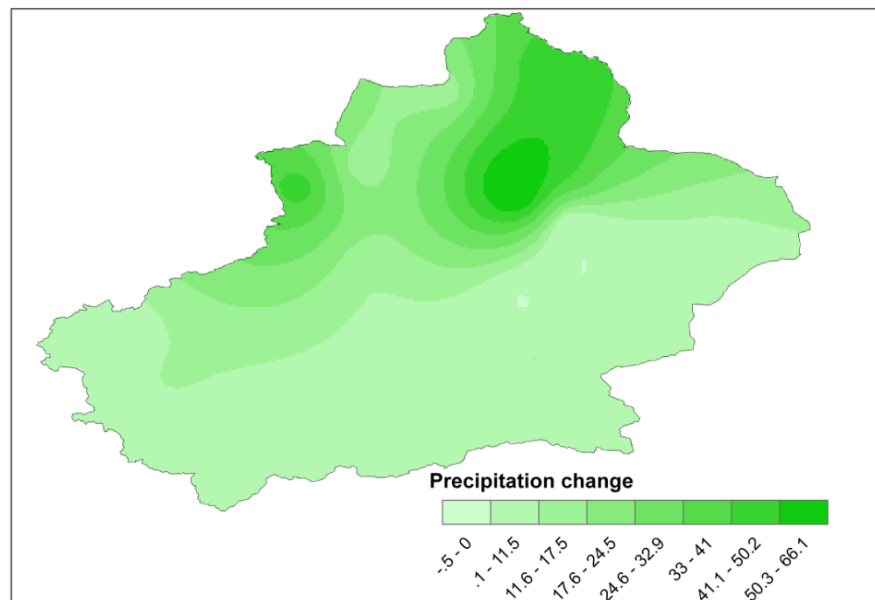
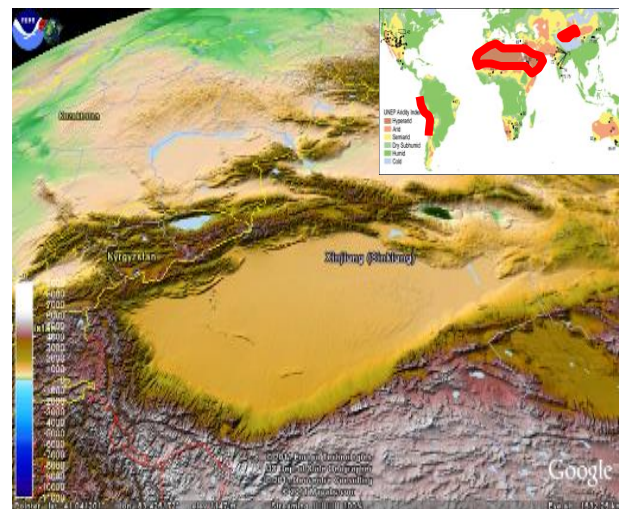
- single-vapor source rainfall (stage 1)
- mixing of two vapor sources (stage 2)
- double-vapor source rainfall with strong rainout effects (stages 3 and 4)

干旱区气候变化水资源效应：

4) 塔里木盆地



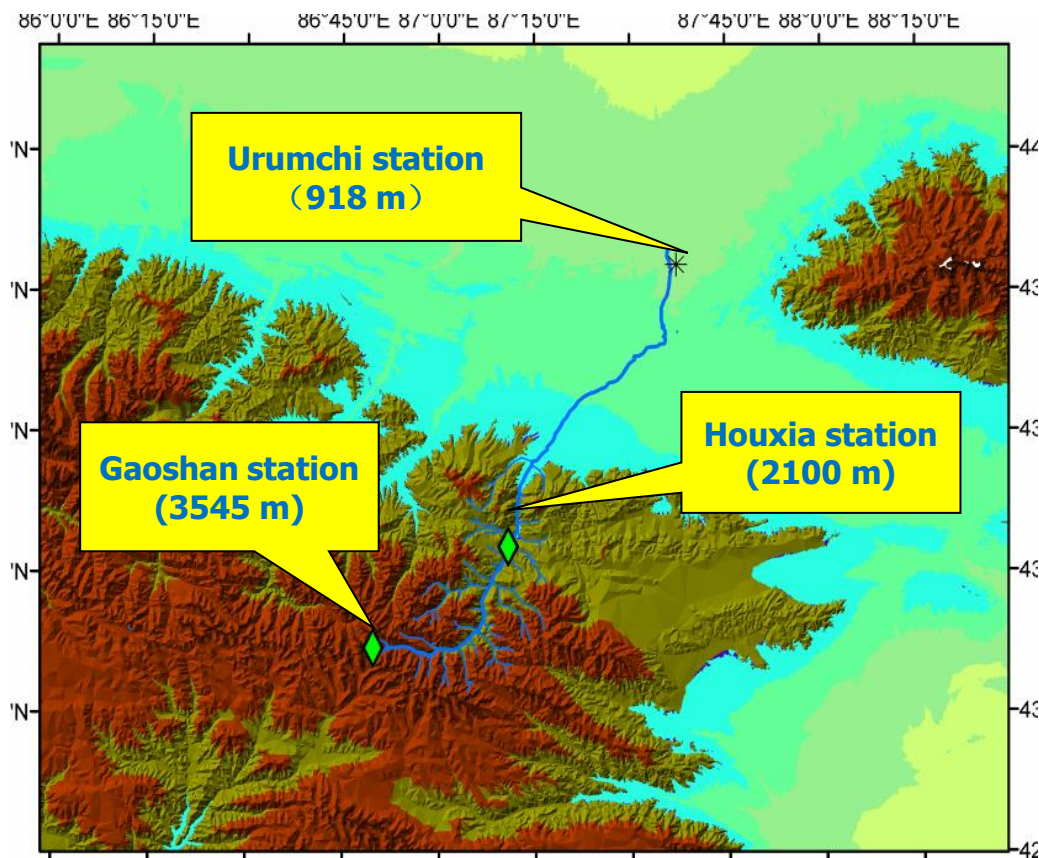
Rising in temperature



Rising in precipitation



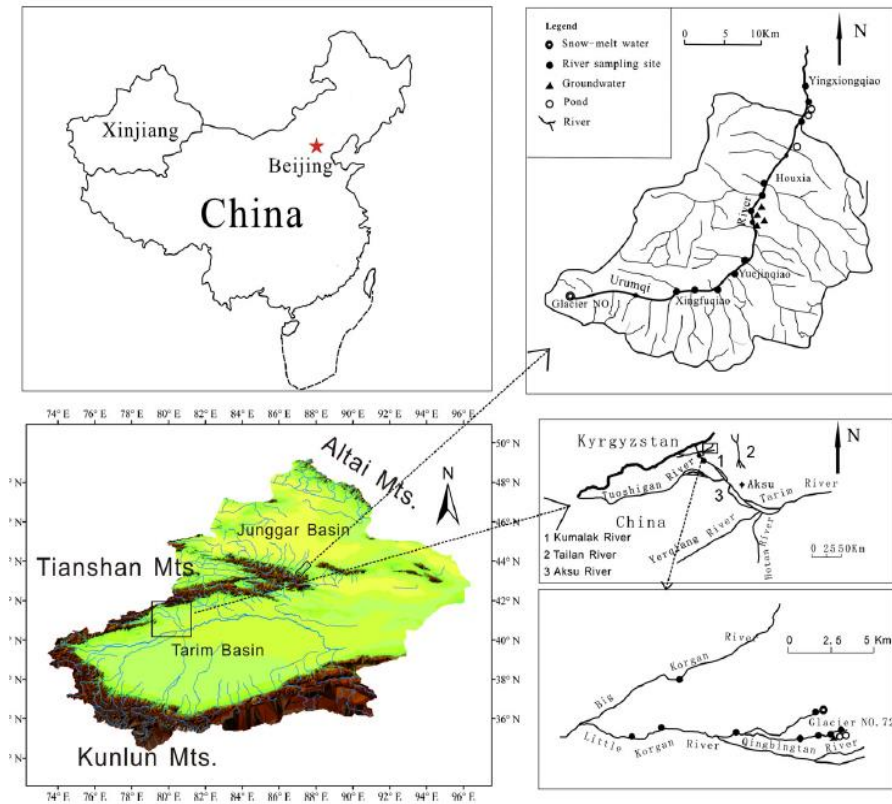
Eventful monitoring of isotopes in precipitation in Tianshan Mountains



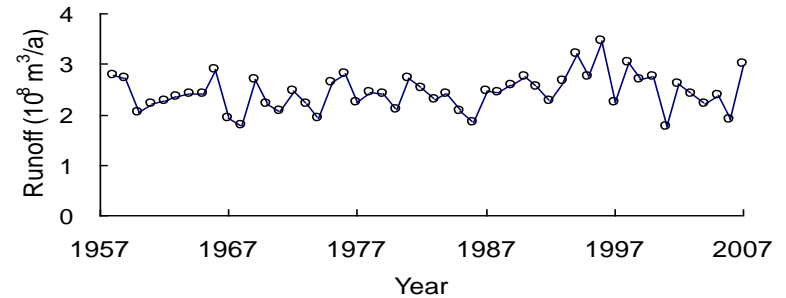
Monitoring stations at various elevation in the Tianshan Mt.



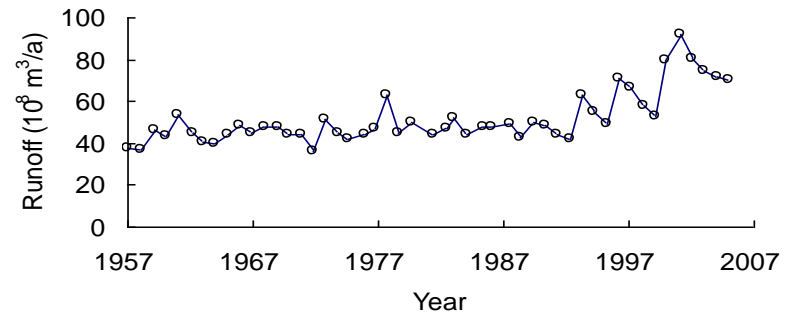
The region is sensitive to climate change, which has been recorded in rivers in the north and south regions, respectively, and heavy floods take place some times during the summer.



Urumqi and Kumalak Rivers in north and South Xinjiang, respectively.



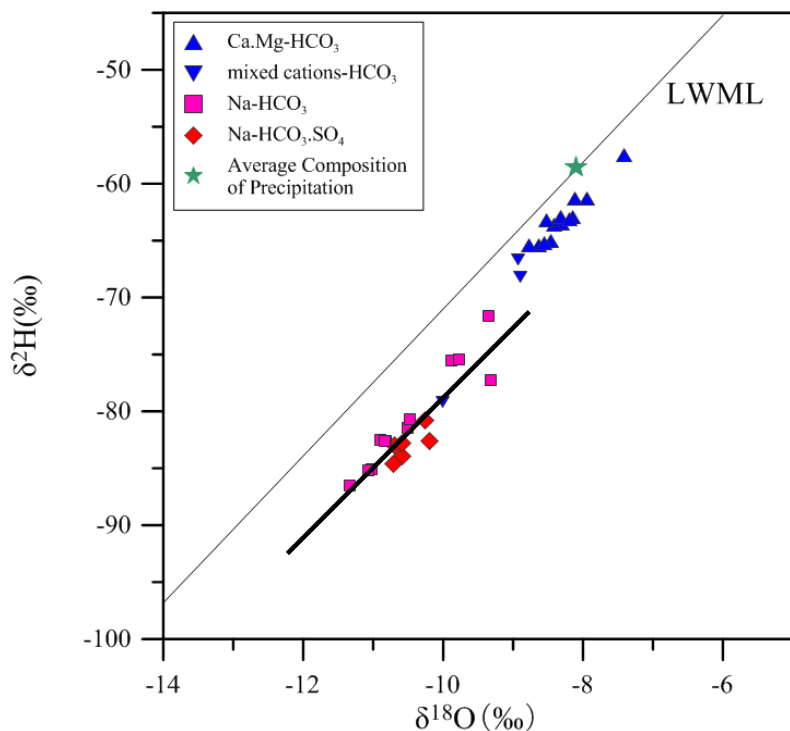
Urumqi River in Northern Xinjiang increases by 10%



Kumalak River in Southern Xinjiang increases by 38.7%

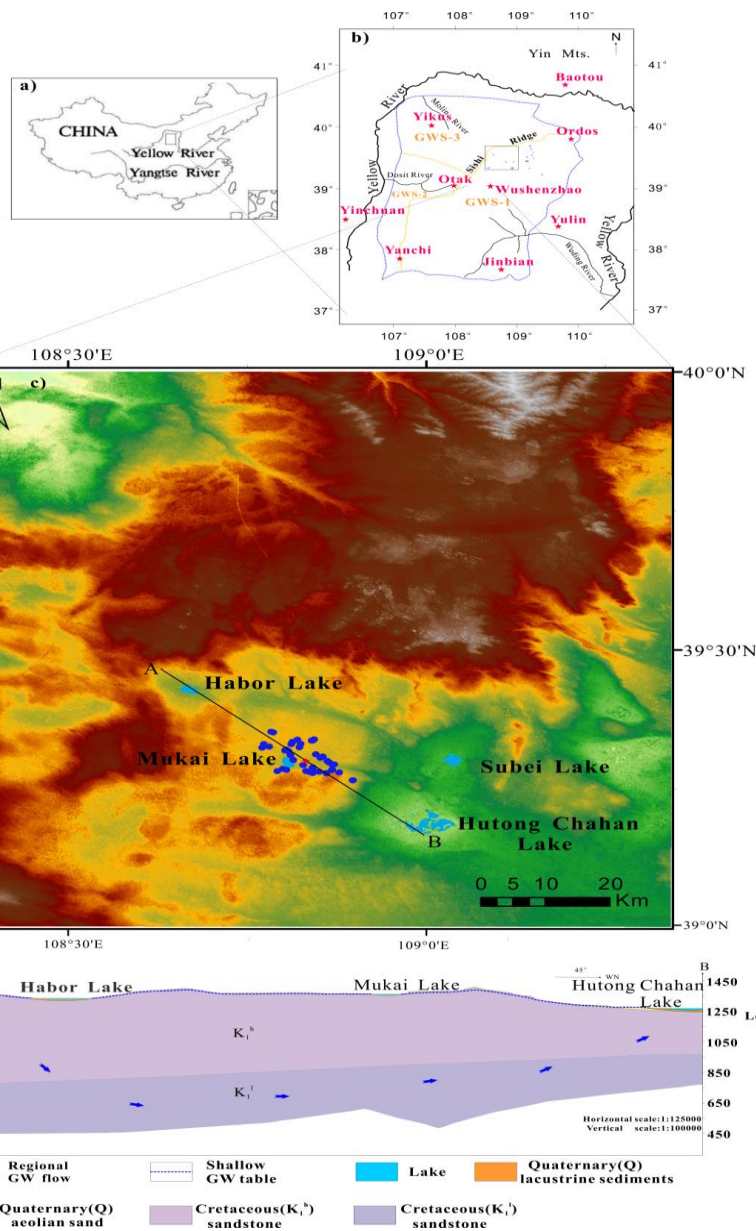
沉积盆地多级次地下水循环：

5) 鄂尔多斯盆地



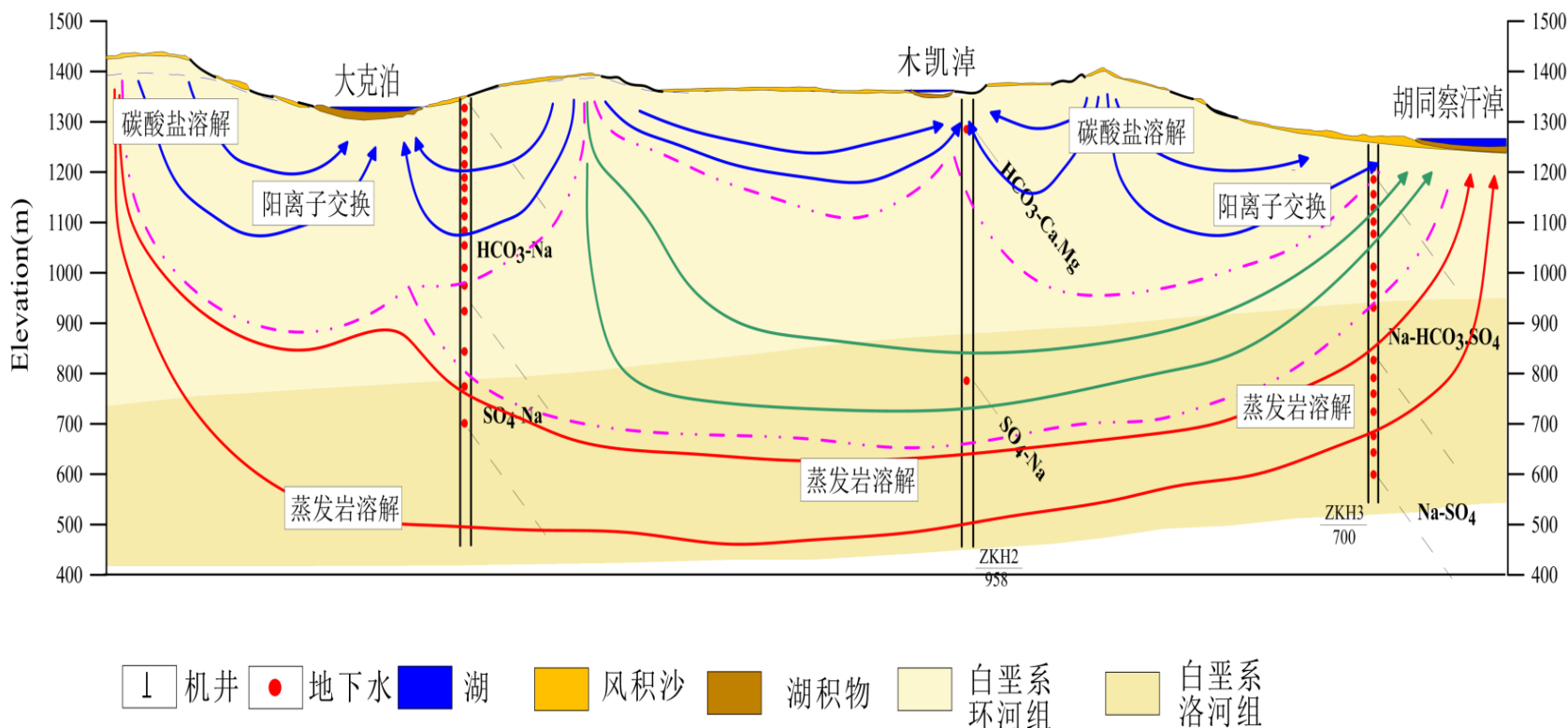
古水线：28万年！

(Lyu and Pang, Water, 2017)





地下水循环对水质的控制作用

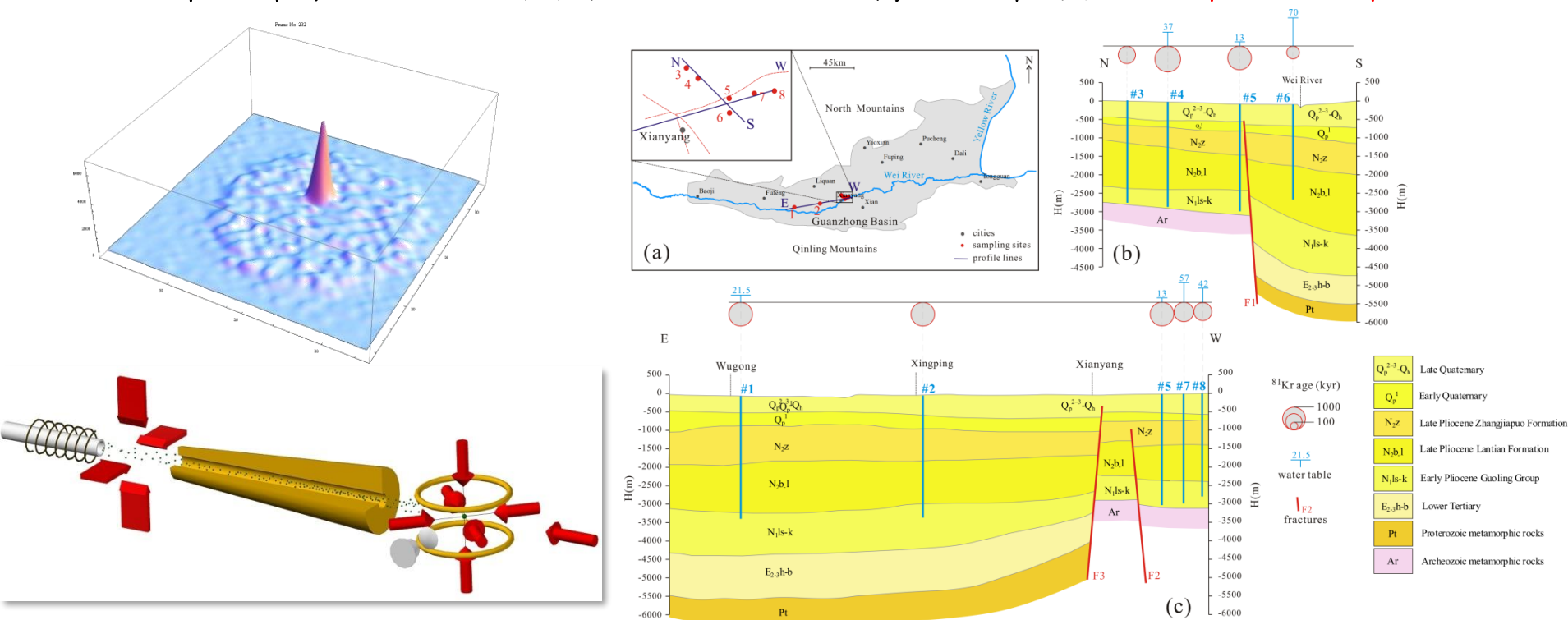


(Lyu and Pang, Water, 2017)

与氦气相关的水循环动力学

6) 关中盆地地热水定年

采集关中盆地2500米~3500米深地热井的气体样品 (N_2 为主要组分)，采用世界领先的原子阱痕量分析技术 (ATTA)，实现了地下水定年。结果显示，关中盆地地热流体中的稀有气体He主要源于壳内放射性成因， ^{81}Kr 年龄在30万年~130万年之间。



原子阱痕量分析技术示意图

关中盆地采样点 (a) ; E-W (b) 及S-N (c) 向地质剖面及 ^{81}Kr 年龄 (Li & Pang et al., 2017)

中国作者的国际论文： 科研进步

Water isotopes

Results found: 1714

Sum of the Times Cited [?]: 28793

Sum of Times Cited without self-citations [?]: 26773

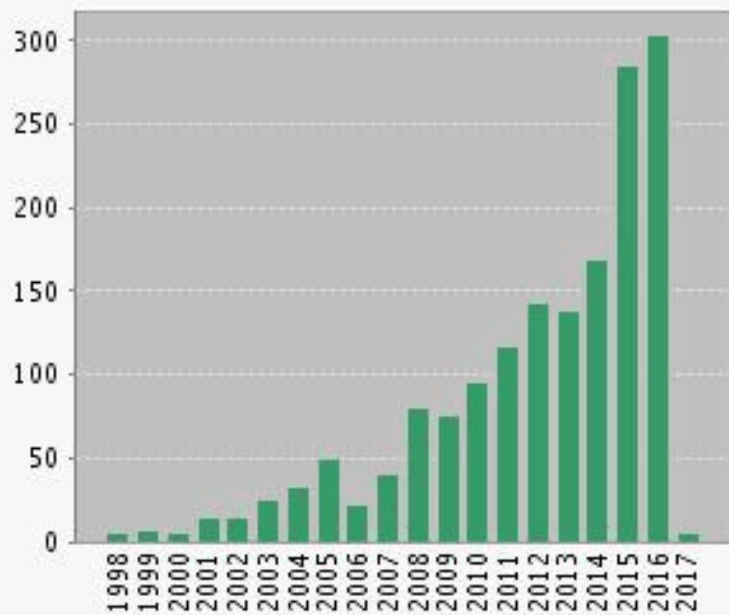
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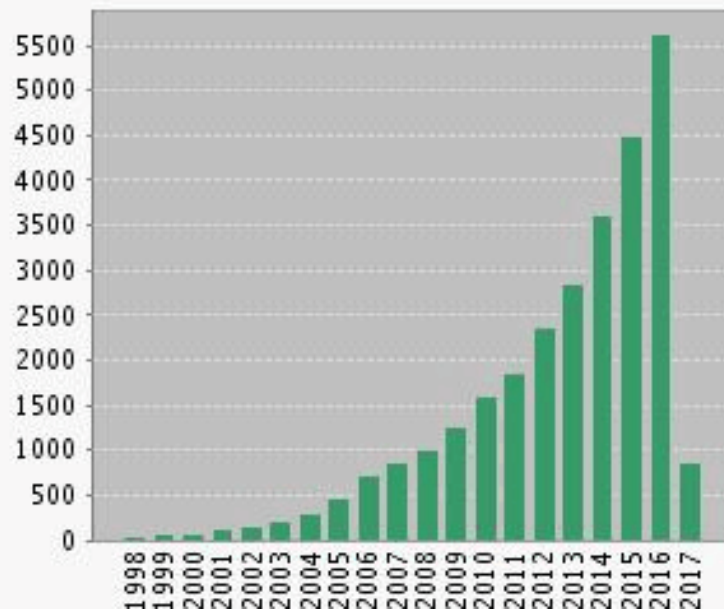
Average Citations per Item [?]: 16.80

h-index [?]: 71

Published Items in Each Year



Citations in Each Year



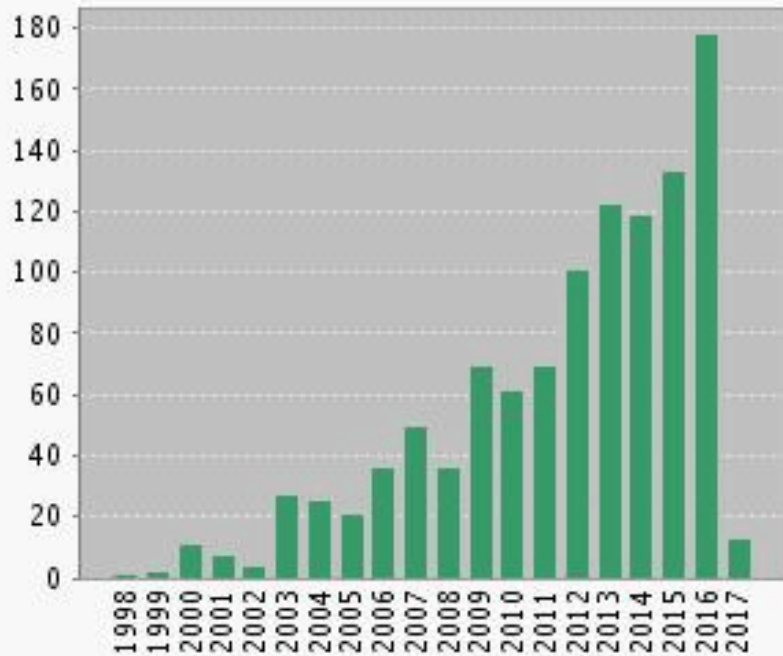
Source: Web of Science

中国作者的国际论文

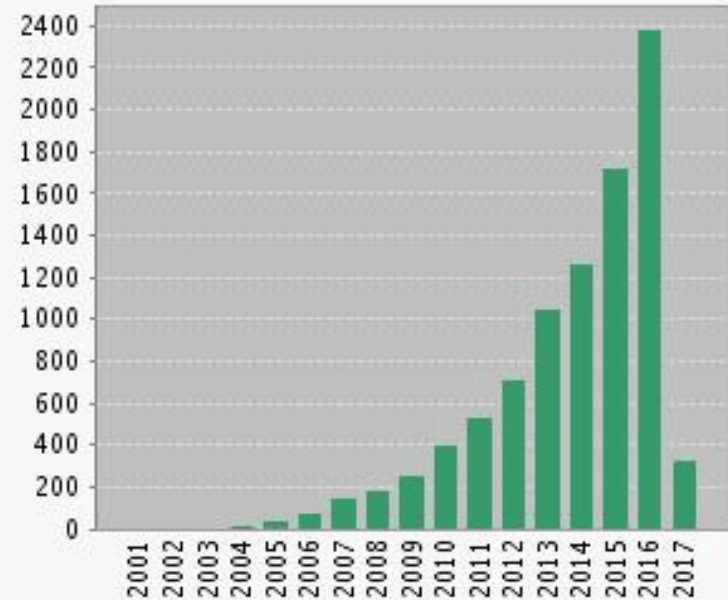
- Groundwater recharge

Results found	: 1091
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Citing Articles [?]	: 6177
Citing Articles without self-citations [?]	: 5620
Average Citations per Item [?]	: 8.41
h-index [?]	: 43

Published Items in Each Year



Citations in Each Year



INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
October 9-12, 2006 Beijing, China

水的现状与未来
Present and Future

主办: 中国地质调查局 IAH 中国分会
Organized: China Center of Geology IAH China Chapter of 1998



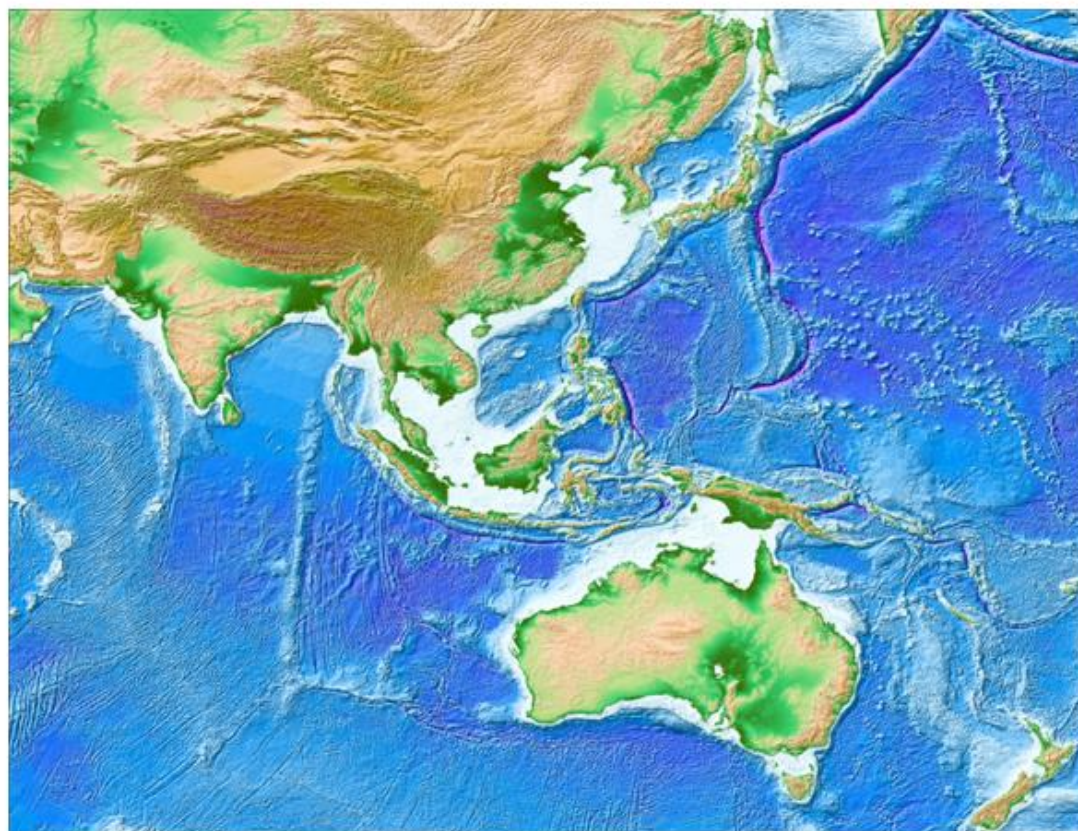
国际合作：单边、多边、一带一路！！

Ongoing Projects with the IAEA:

- 1、 A CRP (coordinated research program) project on precipitation isotopes and climate change**
- 2、 A CRP project on urban water supply as affected by environmental changes**
- 3、 A TC (technical cooperation) project for Asia and the Pacific region: Enhancing regional capacity in groundwater management using isotope techniques**



2018 IAEA/RCA Technical Workshop on Ground Water Recharge and Dynamics Using Isotopic Techniques



新一轮合作项目
RAS7035，2020
年已经启动。

IAEA/RCA RAS7030 Assessing
Deep Groundwater Resources
for Sustainable Management
Through the Utilization of
Isotopic Techniques
2016-2019

September 17-21, 2018 @ Beijing, China

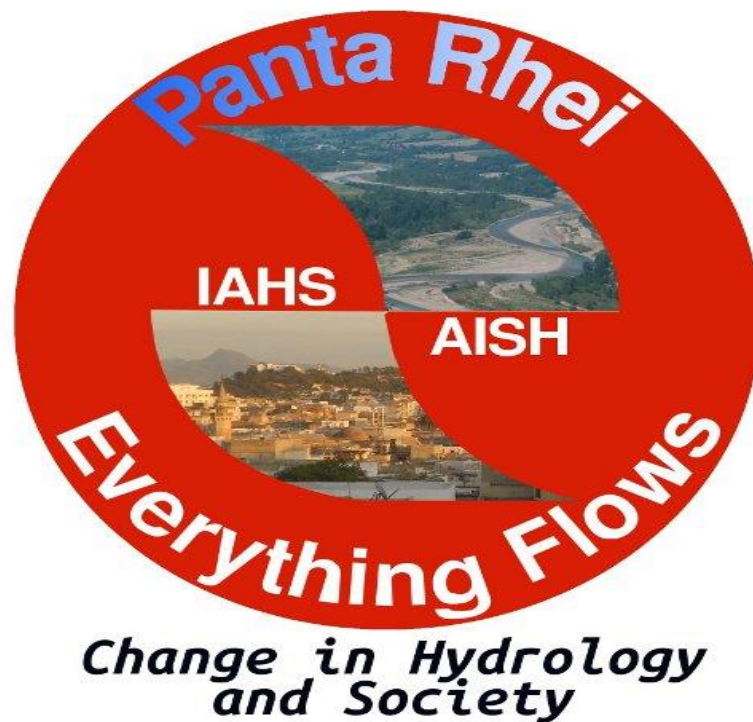
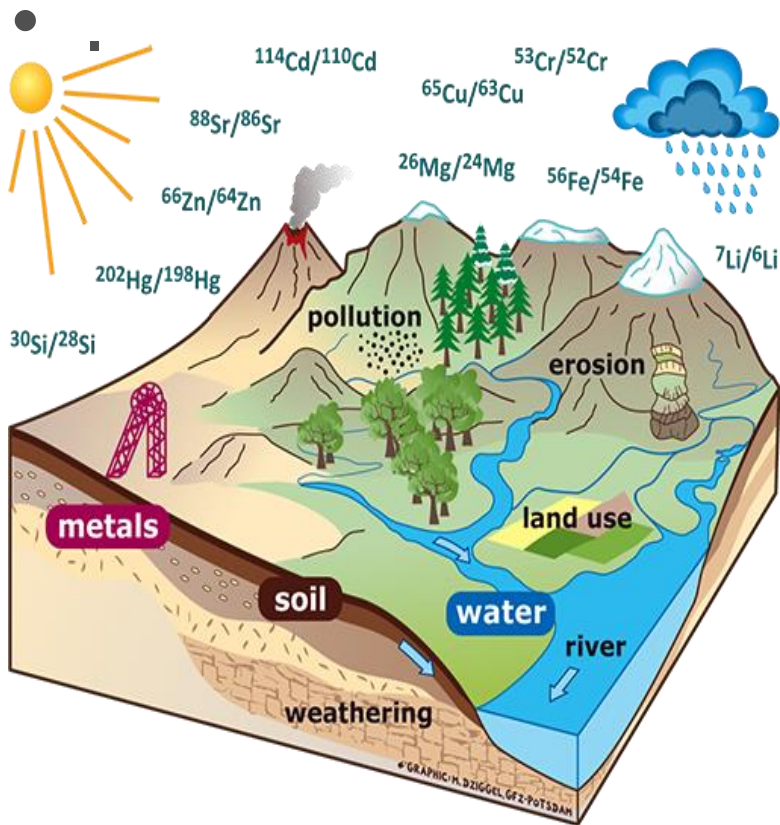


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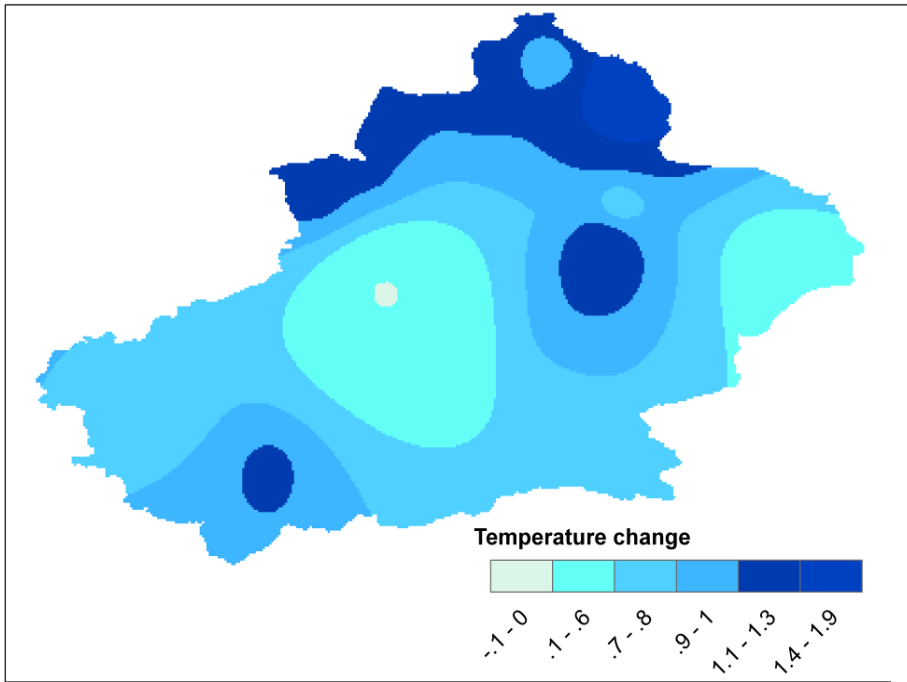
流动着的变化：国际水文科学十年科学发展 规划（2013-2023）



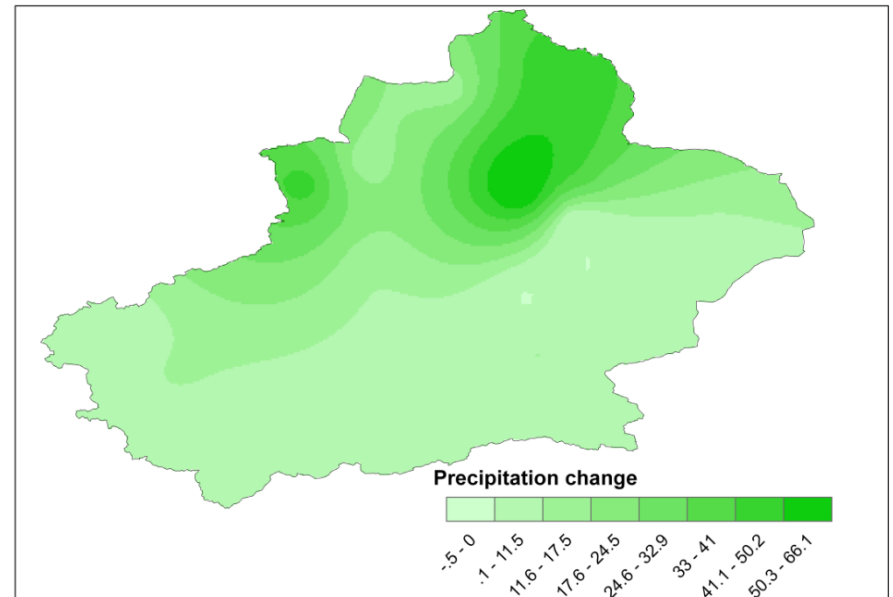
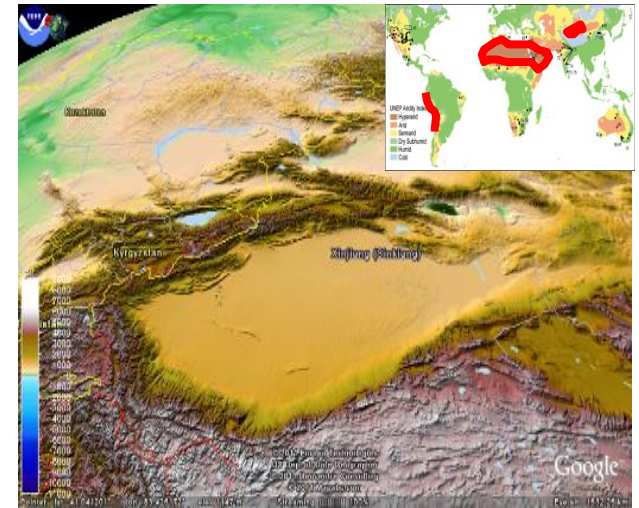
Source: <http://www.isonose.eu/home/>

Source: Montanari et al., Panta Rhei—Everything Flows: Change in hydrology and society—The IAHS Scientific Decade 2013–2022, Hydrological Sciences Journal, 58:6, 1256-1275, DOI:10.1080/02626667.2013.809088

1、气候变化营力



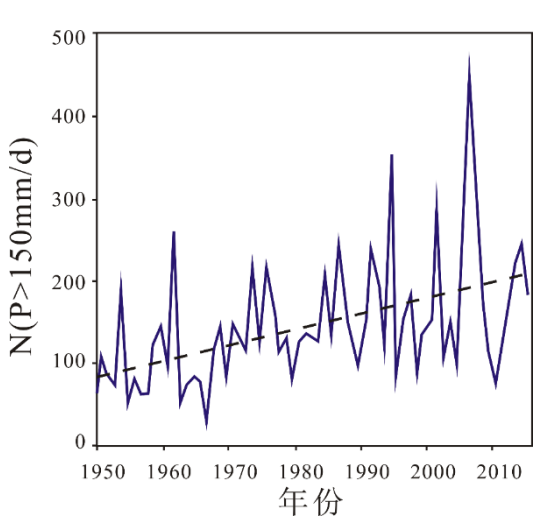
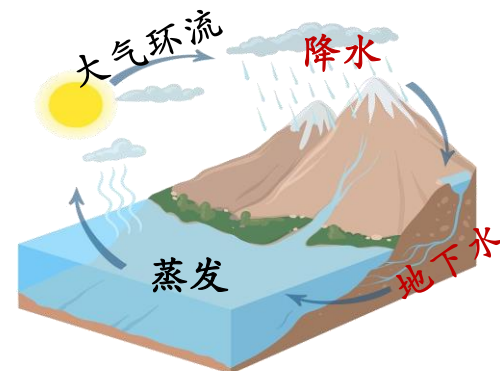
Rising in temperature



Rising in precipitation

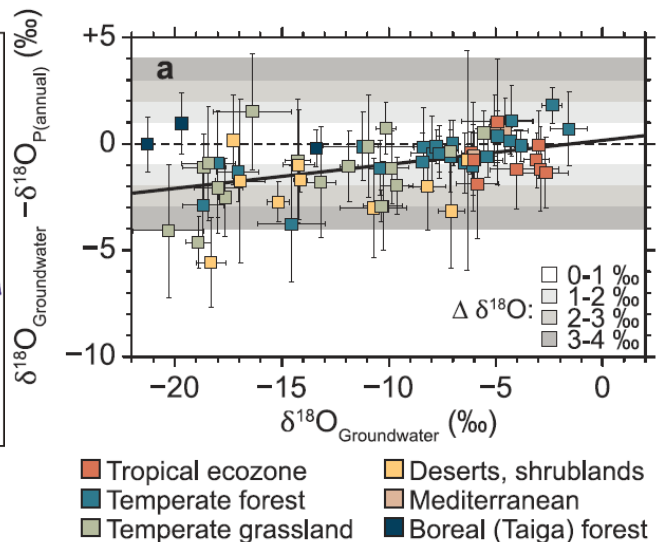
降水-包气带-地下水补给：时间、机理、过程、变化

- 1、降水与地下水之间的同位素信号差异，如何解释？
- 2、气候变化背景下，降水变化（类型、年内分布、雨强等）对地下水补给的影响？
- 3、人类活动影响下，下垫面改变对地下水补给的影响？



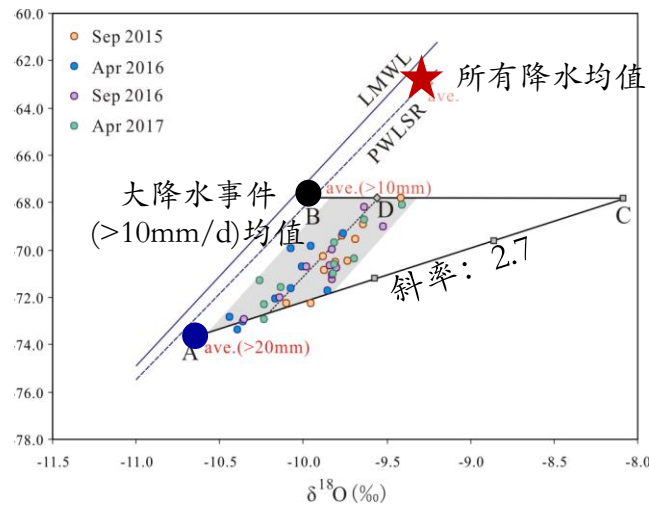
暴雨频率增加

(Roxy et al., 2017, Nat Commun)



地下水与降水之间的同位素差

(Jasechko et al., 2014, WRR)



延庆盆地地下水氕氧关系图

(Li & Pang et al., 2018, J Geophys Res-Atmos)

海相页岩地层水来源及赋存状态

页岩气井生产阶段产生大量地层水（非压裂液），矿化度很高（1-10倍海水），氢氧同位素贫化。

来源假设：

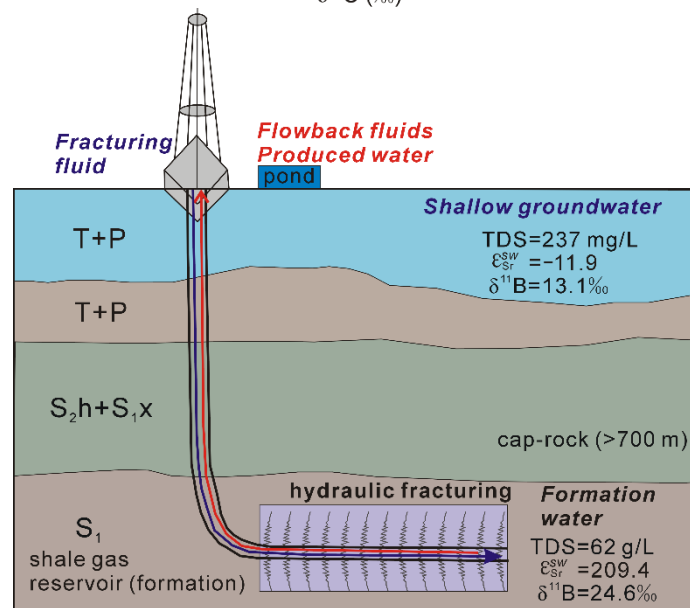
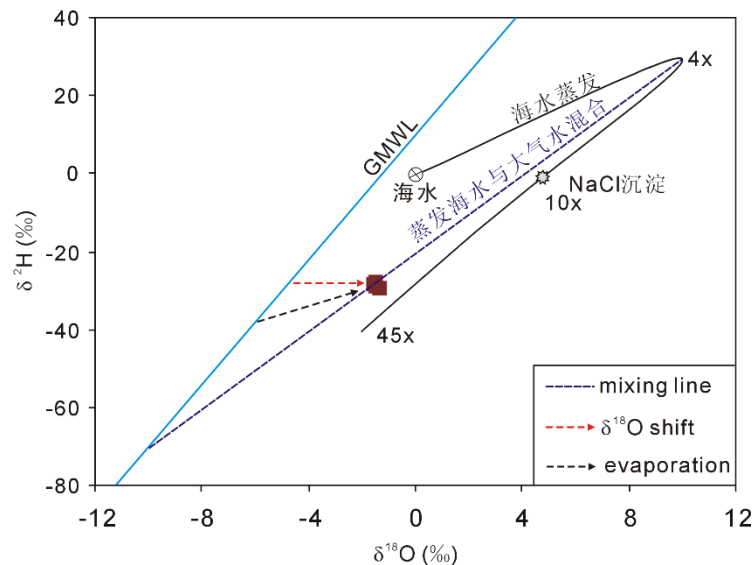
- 1、完全是沉积海水，氢氧同位素组成不在海水及蒸发线上可能是一些地球化学作用所致
- 2、沉积海水（后期受到蒸发作用），再与大气水混合
- 3、完全是大气水成因，并受到蒸发作用或 ^{18}O 漂移

赋存状态：

- 1、如果是孔隙水，则不会大量排出。
- 2、最有可能是裂隙水，可受大气水补给

意义：

水既然是裂隙水，页岩气也可大量在裂隙中赋存和运移。这对页岩气赋存状态及开发提出挑战。

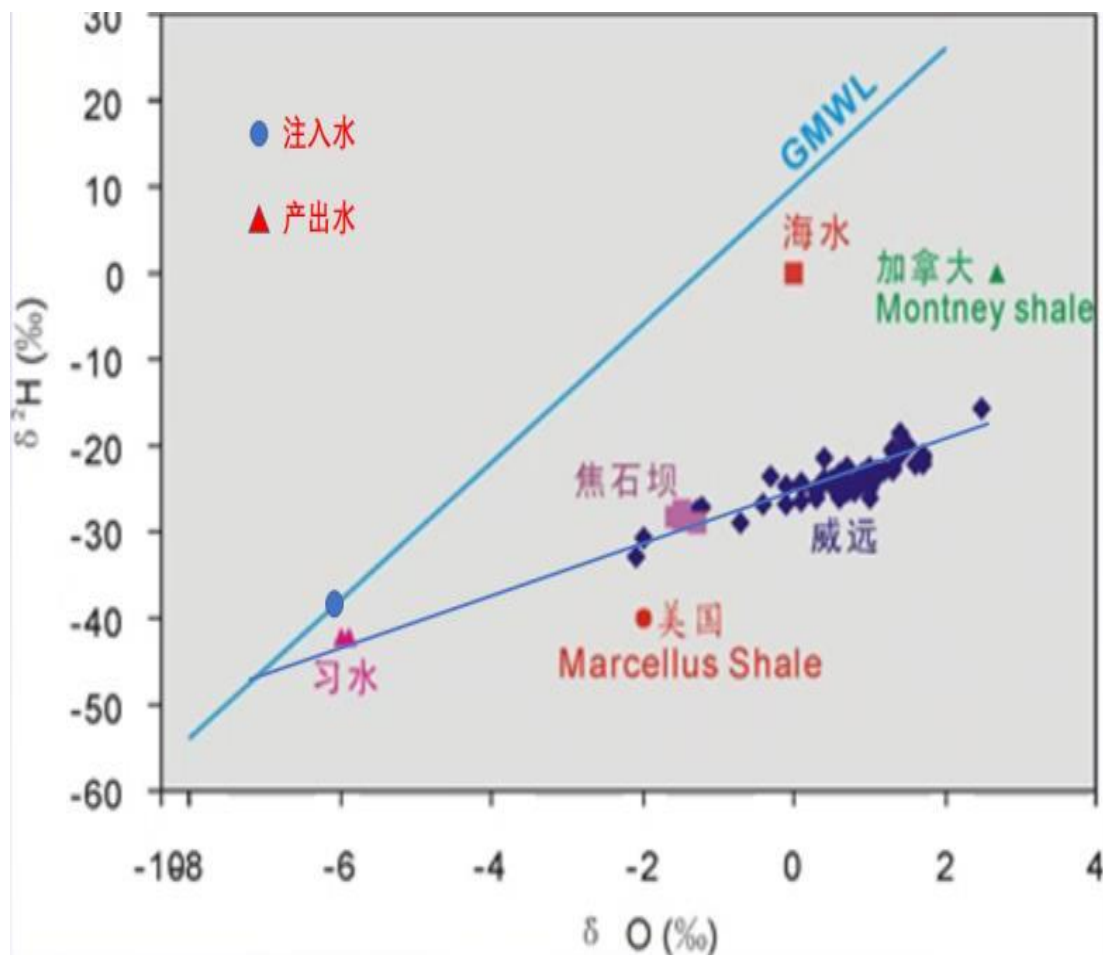


2、人类活动：页岩气开采

神奇的页岩水：

年龄很老，无C-14，
无氙，但是落在雨水
线上。

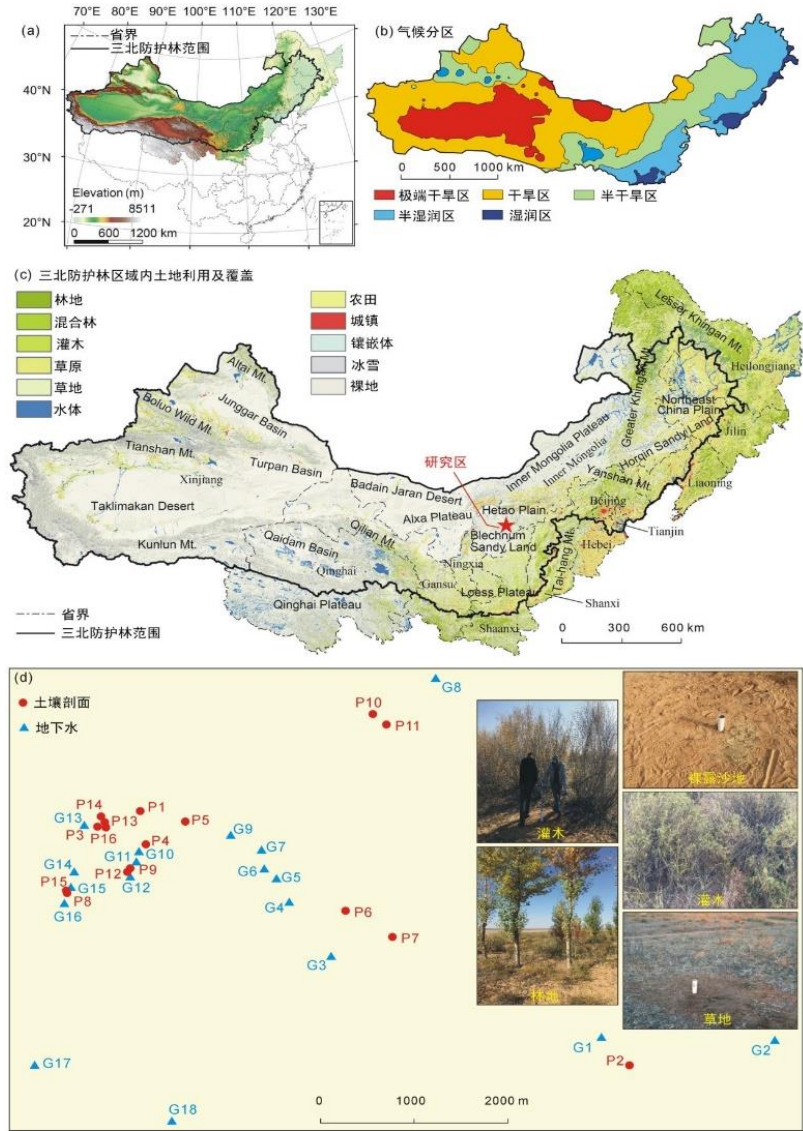
它是怎么形成的？在
致密页岩中是怎么赋
存的？



3、人类活动：退耕还林还草

有些地方成功了，还有些地方有困难。为什么？

对干旱半干旱地区实施的植树造林等生态工程对地下水补给的影响进行系统的评价。





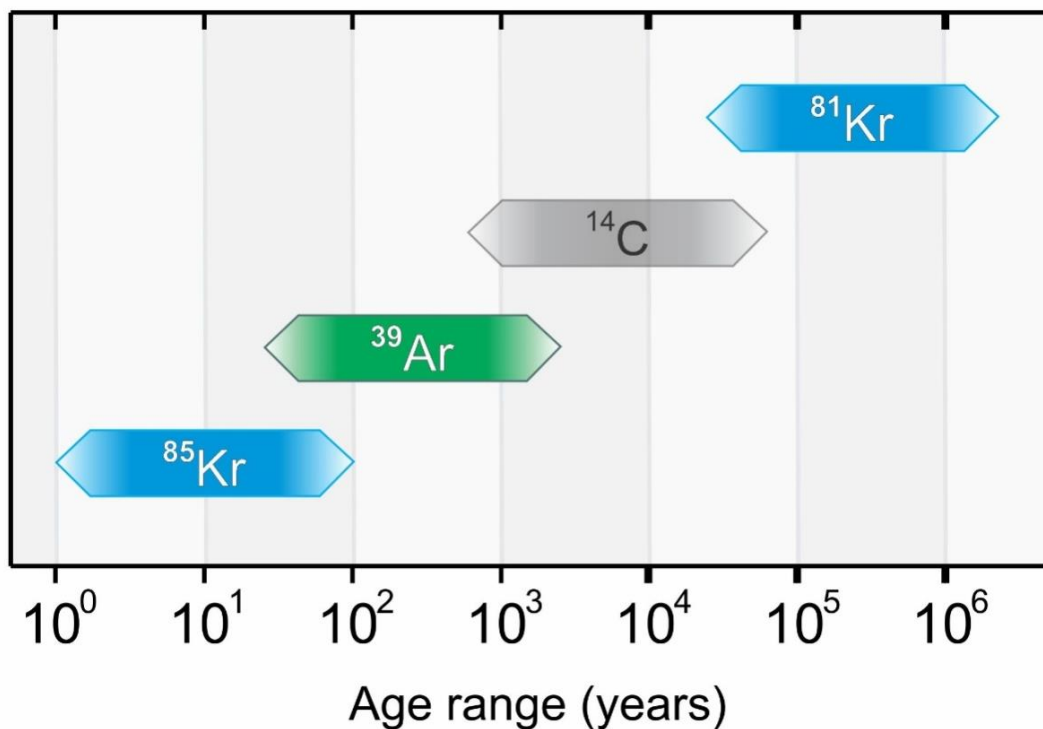
近年来，国际地下水研究呈现两大态势：

- 1) 地下水问题更加严峻，环境与人为因素不断强化，补给减少、水源枯竭、水质恶化、污染多样化的问题层出不穷；
- 2) 以激光技术引领的技术进步使同位素水文学和地下水年代学相关的测试能力得到空前提升。遥感技术也表现不凡。这两大态势为水文地质学创造了难得的发展机遇。

机遇与挑战并存！

放射性气体同位素定年、示踪

- 气体：在大气中分布均匀、稳定
- 惰性：无化学反应，运输机制简单
- 与 ^{14}C 一起，覆盖了从几年到140万年的范围

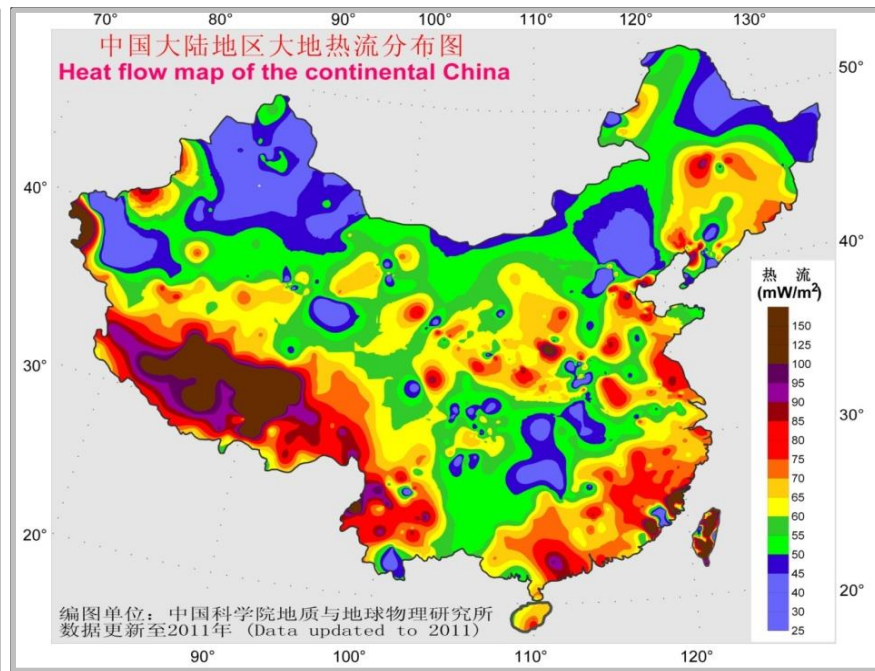


高温地热水循环动力学

高温地热水定年是地热研究的难点之一，迄今青藏高原地热水年龄仍为未知。其原因是高温地热流体的组分来源复杂，以 CO_2 为主要组分，常用定年示踪剂 (^3H 、 ^{14}C 、 ^{36}Cl 等) 易被稀释或富集，导致测年结果失真。



全球地热带分布示意图



中国大陆地区大地热流分布图
(汪集暘等, 2012)

高温地热水循环动力学

在高温地热区开展 ^{85}Kr 、 ^{39}Ar 、 ^{81}Kr 、 ^{14}C 等多种同位素综合测年，建立校正模型，确定高温地热水年龄。

西藏羊八井



西藏羊易



西藏谷堆



云南腾冲



川西康定中谷



川西康定榆林宫





提纲

- 引言：地球系统水循环
- 水循环界面过程的识别
- 水循环的新驱动力
- 结语：机遇与挑战

结语：迈向水循环动力学的同位素研究

- 同位素水文学：机遇与挑战并存；
- 测试技术：从加速器质谱到原子阱单原子激光测量；
- 水循环解码：从原子层面走向量子层面。量子水文学可能成为下一个驿站？



The Isotope Hydrology Group at the IGGCAS, Beijing, China——小月河畔同位素水文学团队





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Thank you!