

# 卫星遥感在地质灾害智能监测中的应用

胡燮 Hu, Xie

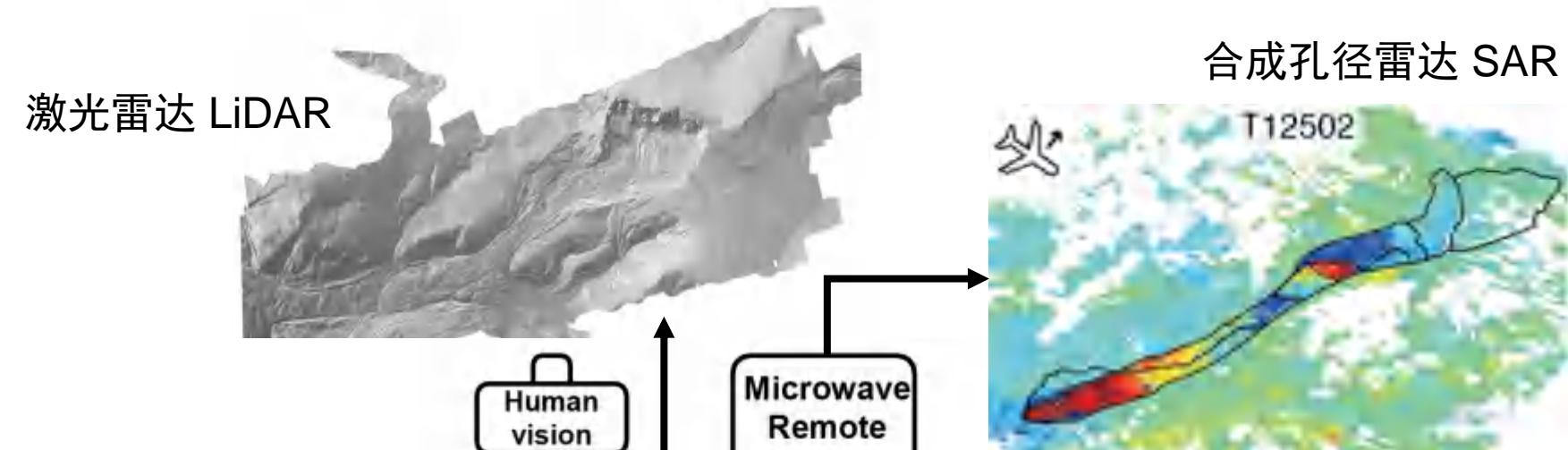
研究员

北京大学城市与环境学院

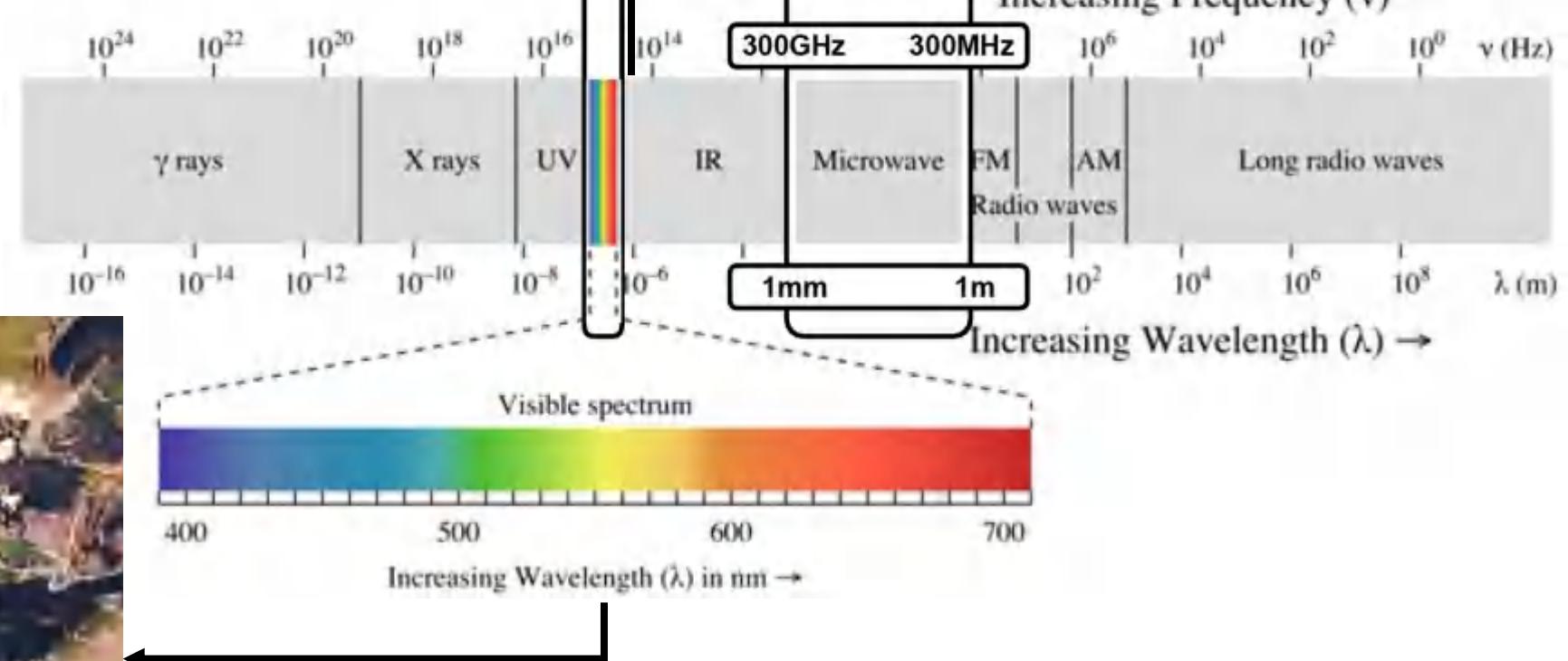
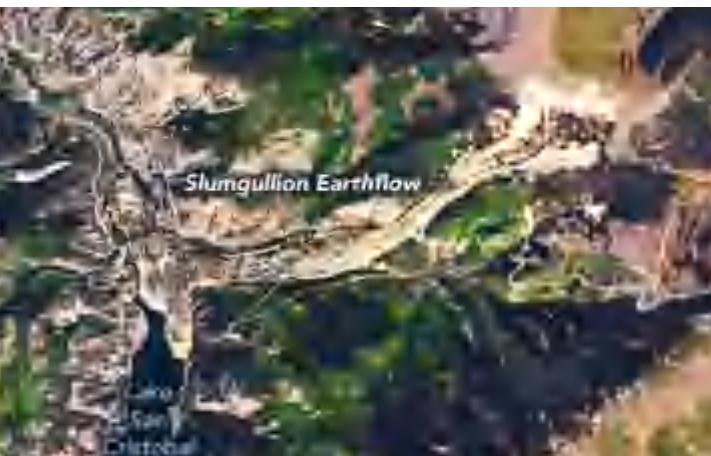
人社部高级研修班  
南京  
10/21/2023

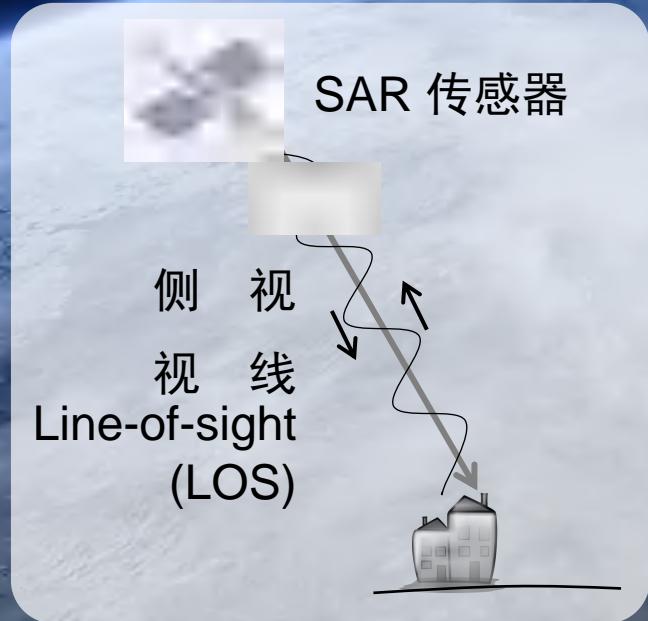
# 遥感大数据

- 多平台  
空 - 卫星  
天 - 航天飞机；无人机  
地 - 地基
- 多波段
- 多时空分辨率
- 数据积累



可见光 Optical  
SfM (Structure from Motion)

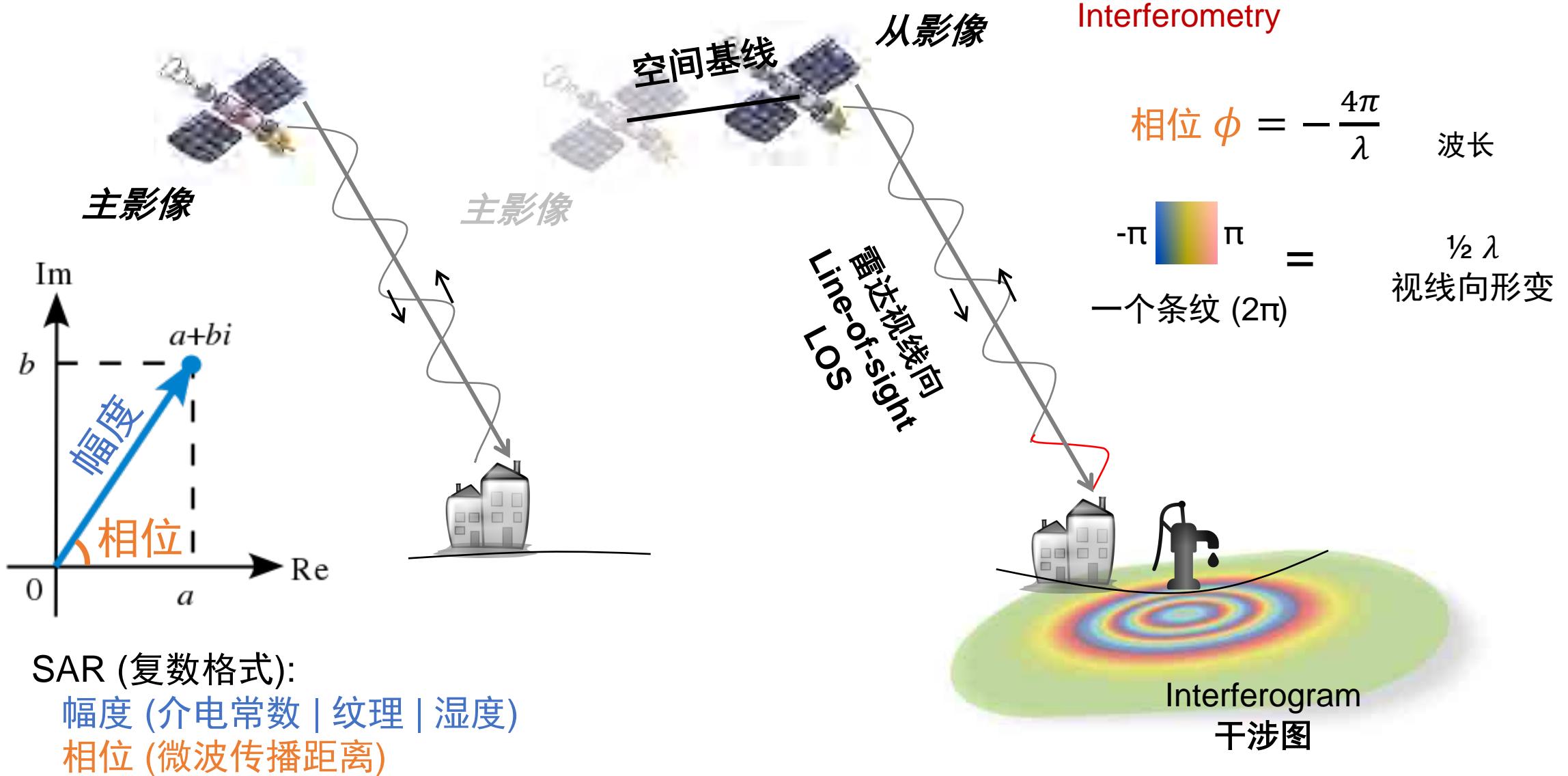




# 合成孔径雷达 Synthetic Aperture Radar (SAR)

全天候&时 | 大范围 | 规律重访周期 | 毫米级形变测量精度 | 低成本

# 基于SAR相位信息的干涉测量 InSAR



## 干涉相位组成

地表形变

大气干扰

轨道误差

地形误差

噪音

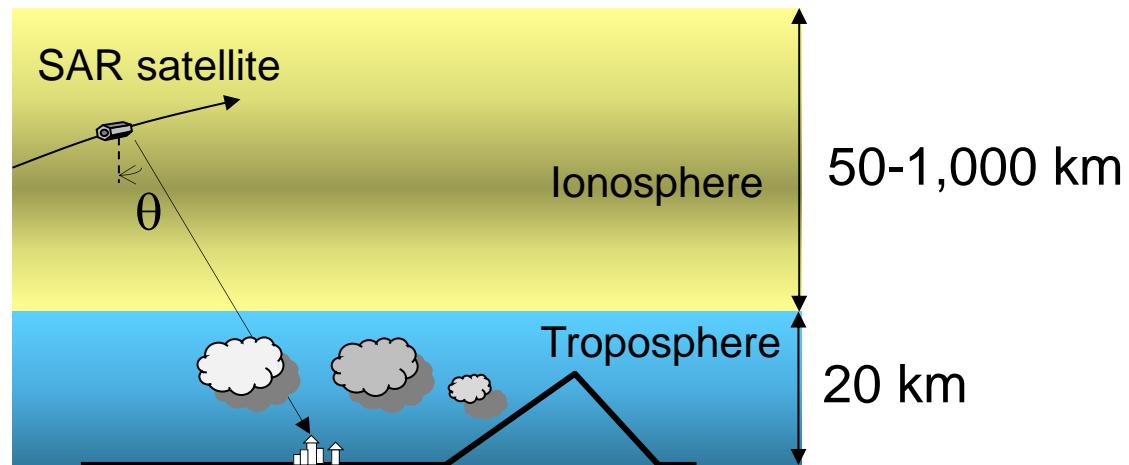
$$\Delta\phi_{ifg} = \Delta\phi_{def} + \Delta\phi_{atmosphere} + \Delta\phi_{orbit}^{\varepsilon} + \Delta\phi_{topography}^{\varepsilon} + \Delta\phi_{noise}$$



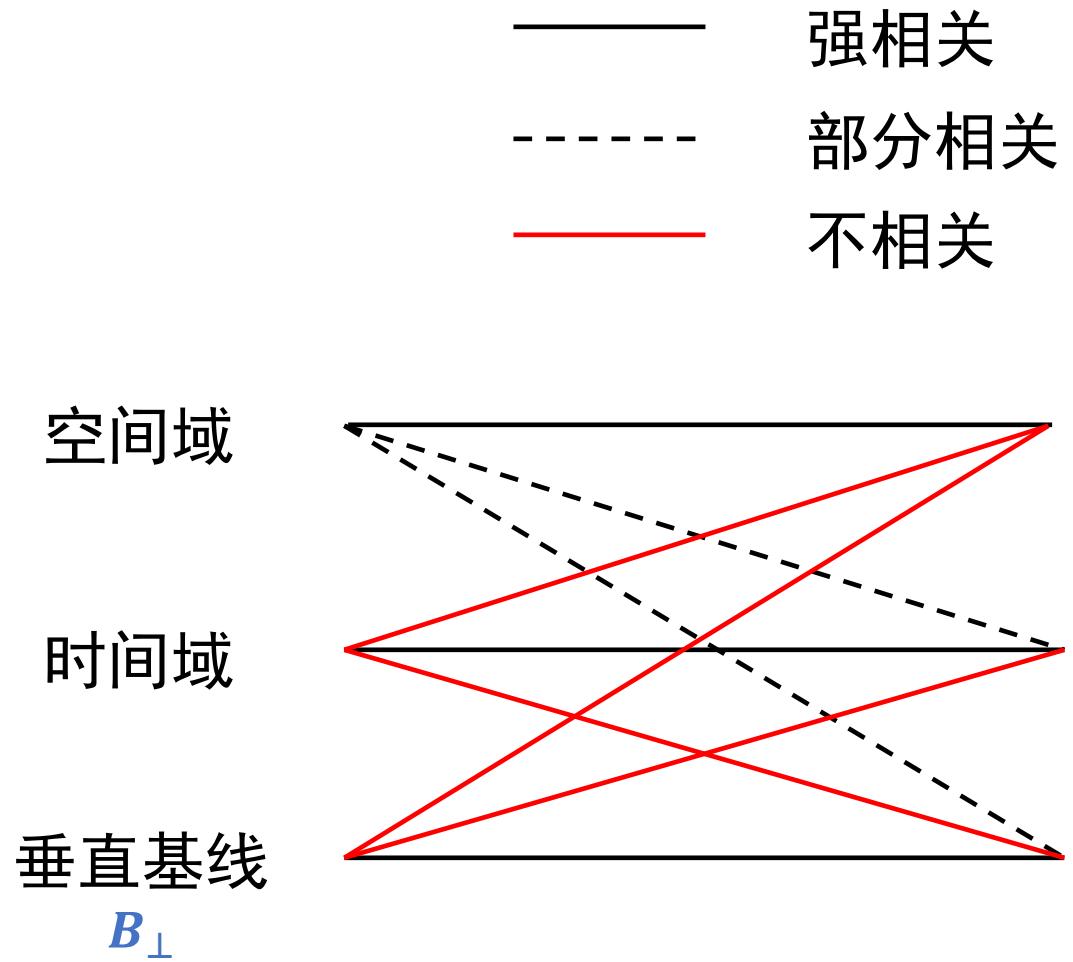
对流层 - 信号延迟  
电离层 - 信号提前



数字高程模型 DEM



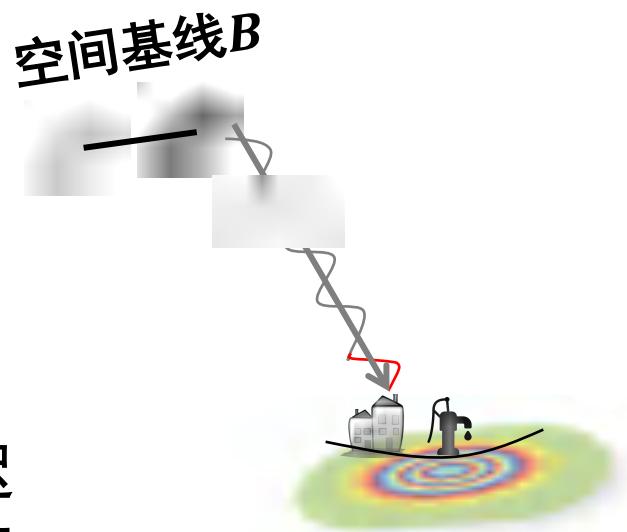
# 干涉相位时空特性



大气延迟  
轨道误差

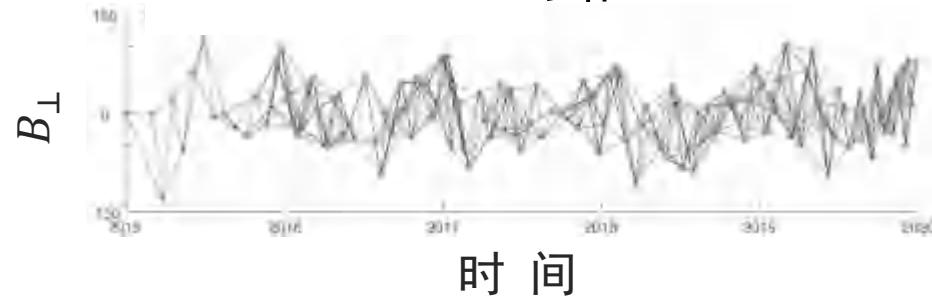
地表形变

地形误差  $\Delta\phi_{topo}^{\varepsilon} = -\frac{4\pi}{\lambda} \frac{\mathbf{B}_{\perp} h^{\varepsilon}}{R \sin \theta}$



# 时序干涉测量分析

InSAR 网络



空间域低通滤波

时间域高通滤波



$$\Delta\phi_{topo}^{\varepsilon} = -\frac{4\pi}{\lambda} \frac{B_{\perp} h^{\varepsilon}}{R \sin \theta}$$

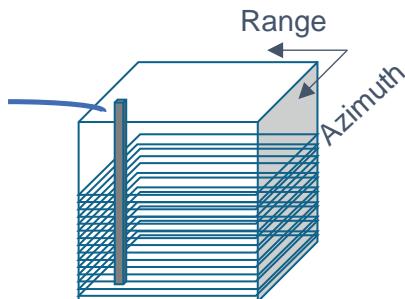
$$\Delta\phi_{ifg} = \Delta\phi_{def} + \boxed{\Delta\phi_{atmosphere} + \Delta\phi_{orbit}^{\varepsilon}} + \Delta\phi_{topography}^{\varepsilon} + \Delta\phi_{noise}$$



天气模型  
选择性叠加

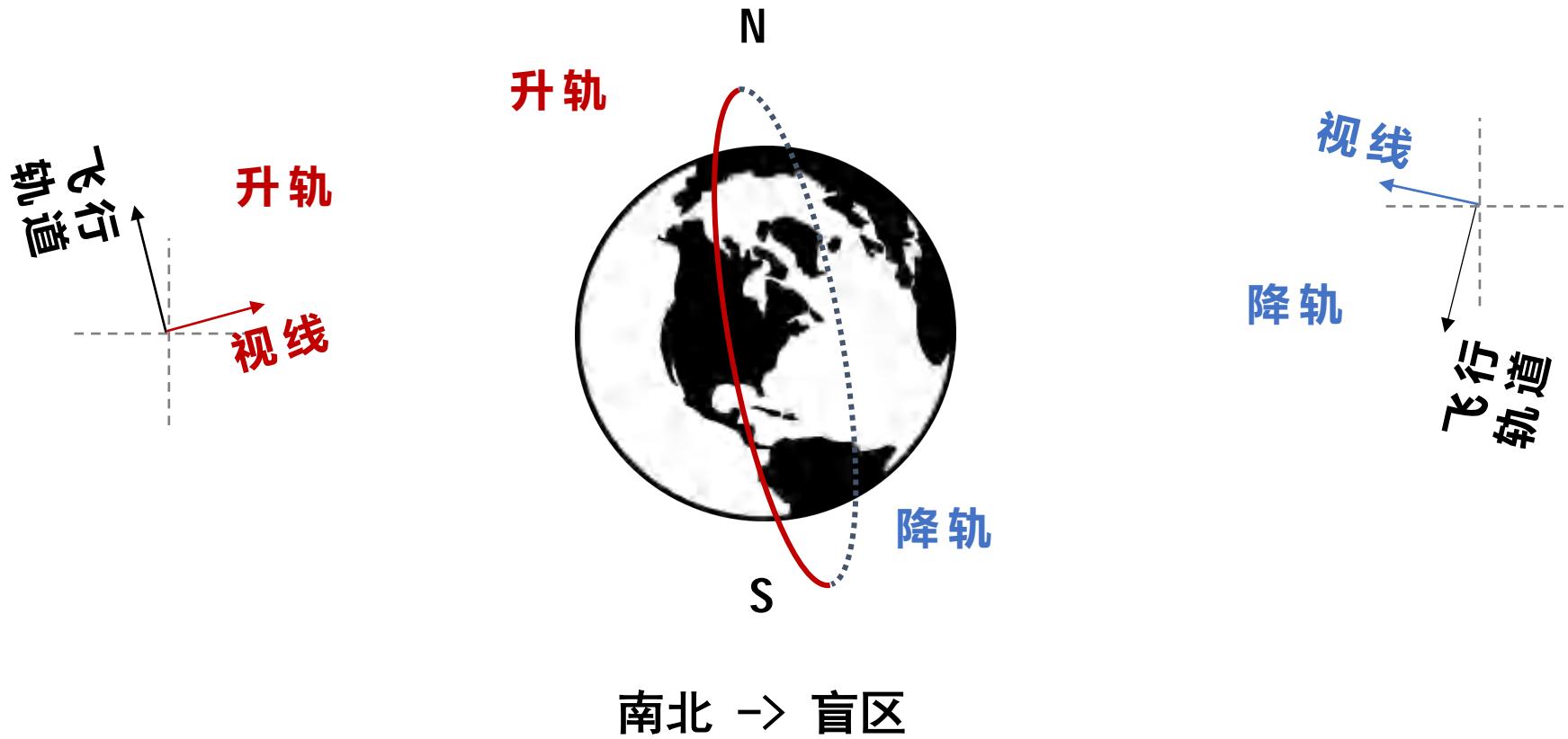
...

反演  
 $G \cdot m = d$

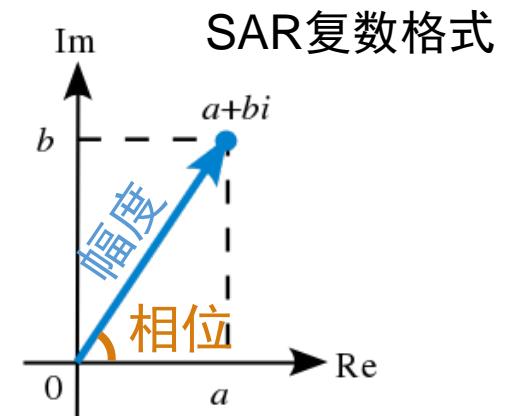
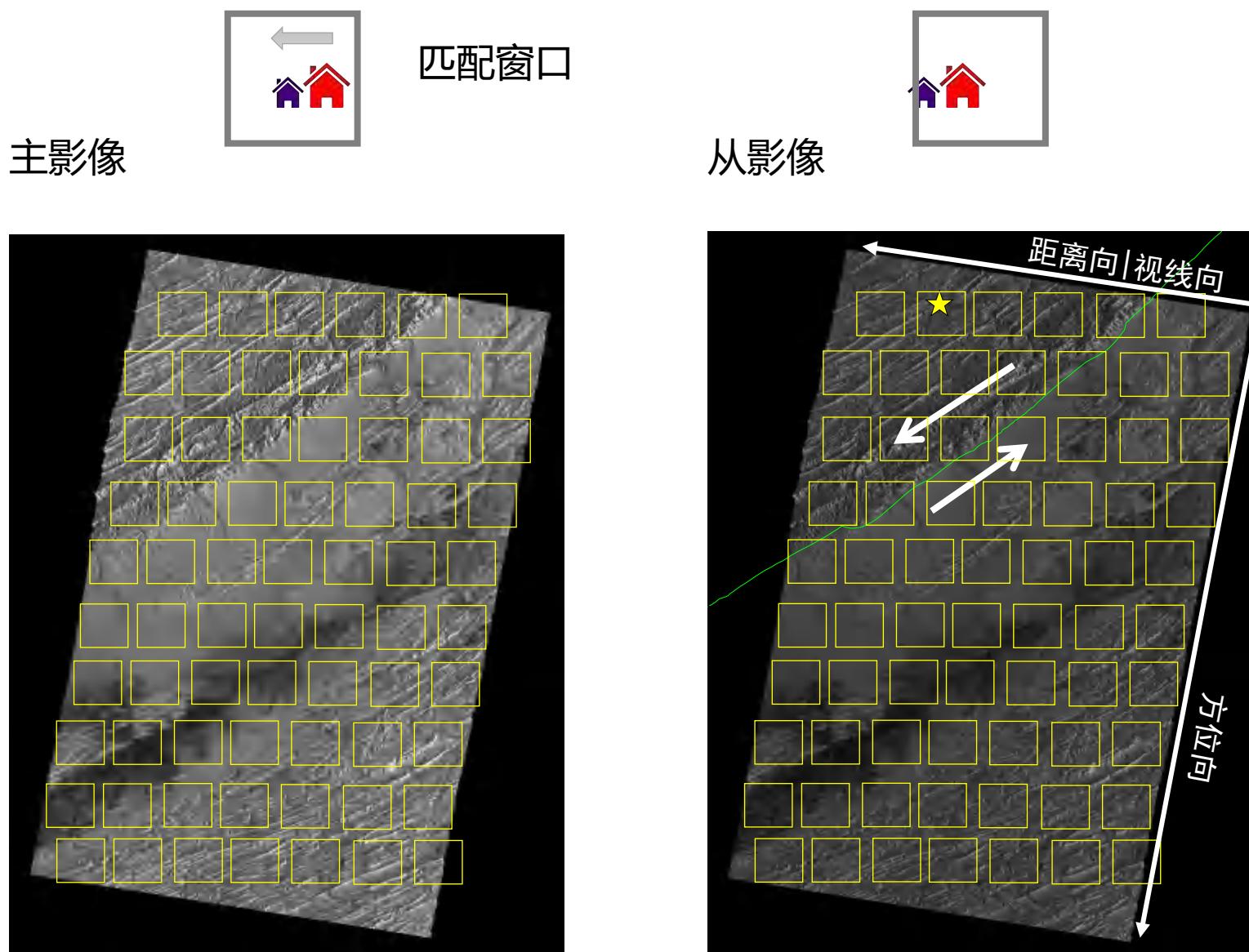


4D 形变 = 3D 空间 + 1D 时间

## 传统干涉测量InSAR的局限性



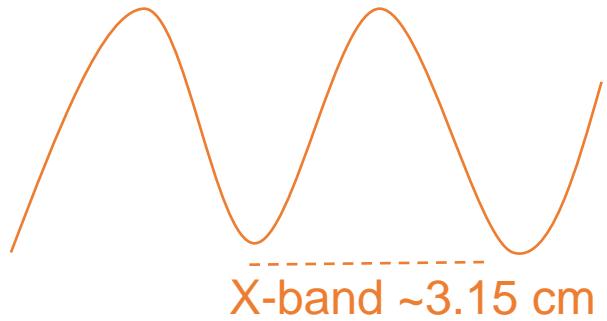
# 基于SAR幅度信息的像素偏移追踪 Pixel Offset Tracking (POT)



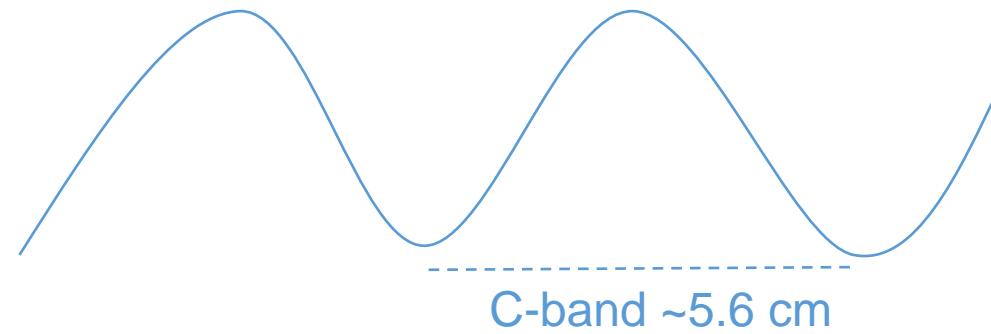
- 2D 测量
- 精度:  $1/20^{\text{th}}$  像素单元
- 适用于米级大形变(同震)

# SAR 卫星微波波段

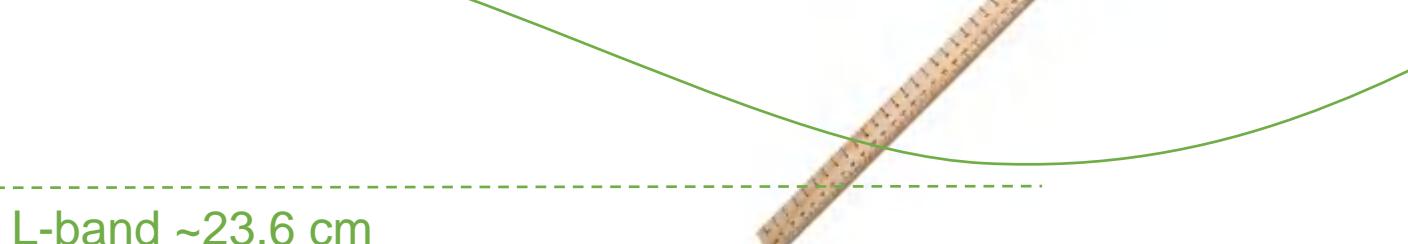
TerraSAR-X (Germany)  
COSMO-SkyMed (Italy)  
PAZ (Spain)



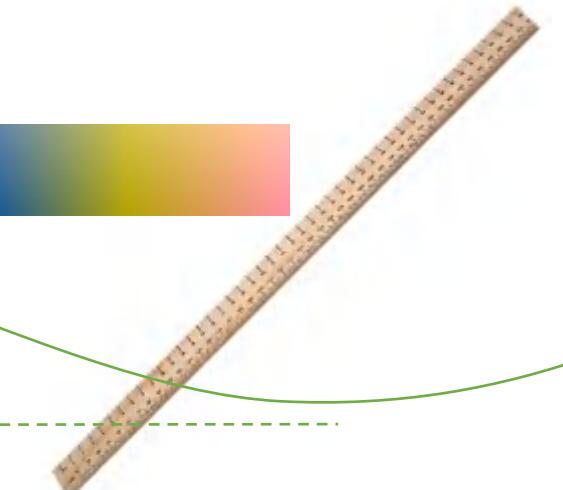
ERS-1/2 (ESA)\*  
ENVISAT ASAR (ESA)\*  
RADARSAT-1/2 (Canada)  
Sentinel-1A/B (ESA)



JERS-1 (Japan)\*  
ALOS-1 PALSAR-1 (Japan)\*  
ALOS-2 PALSAR-2 (Japan)

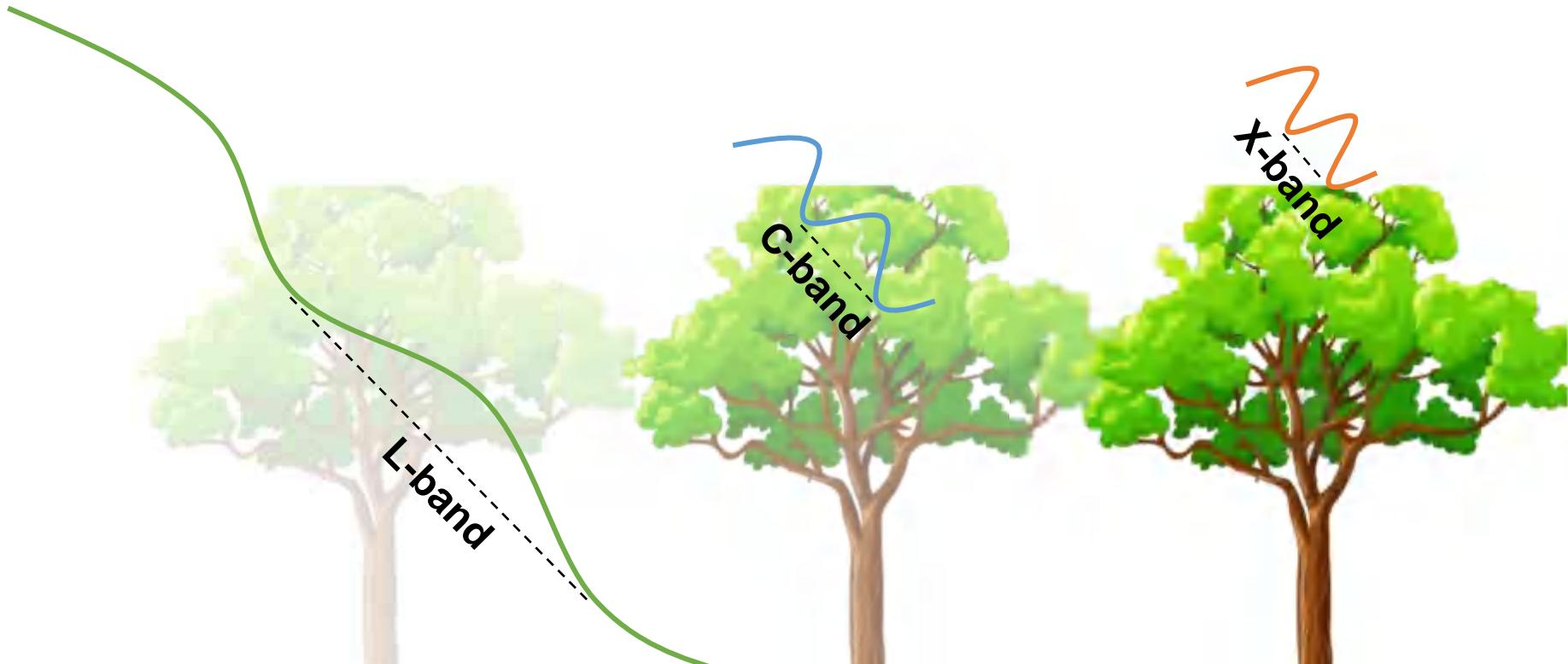


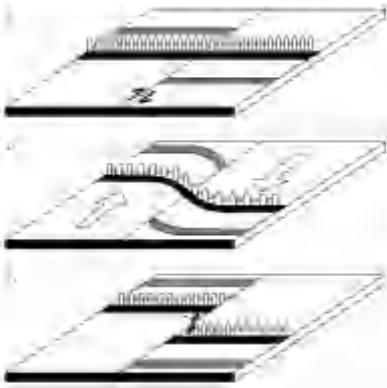
$-\pi$   $\pi$  =  $\frac{1}{2} \lambda$   
一个条纹 ( $2\pi$ ) 视线向形变



\* 下划线卫星已退役

## 微波电磁波穿透性

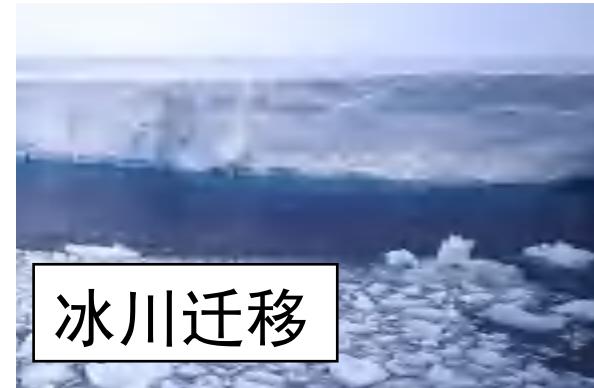




地震周期



地陷



冰川迁移



冻土消融



滑坡

# 自然灾害

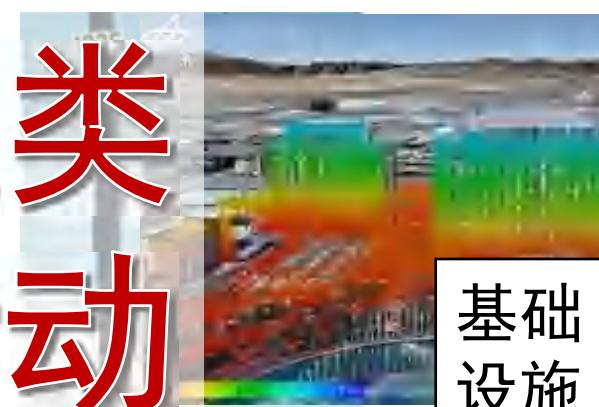


洪涝

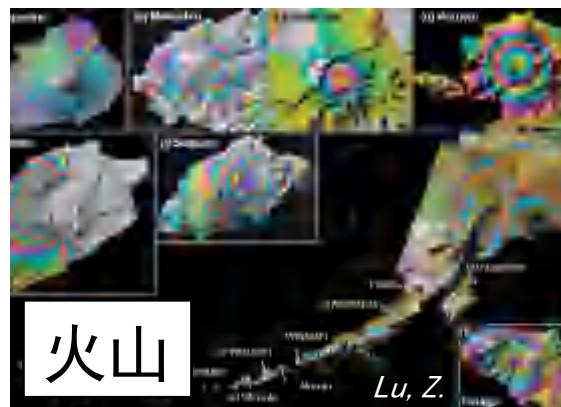


采矿

# 人类活动



基础设施变形



火山



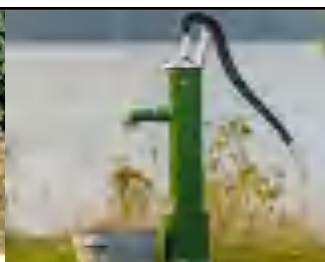
堰塞湖



油气

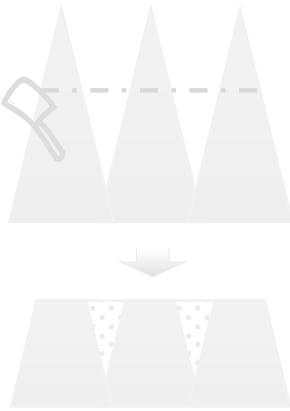


地下水开采





山体滑坡  
粘塑性滑坡  
热融滑塌陷  
易发性评价



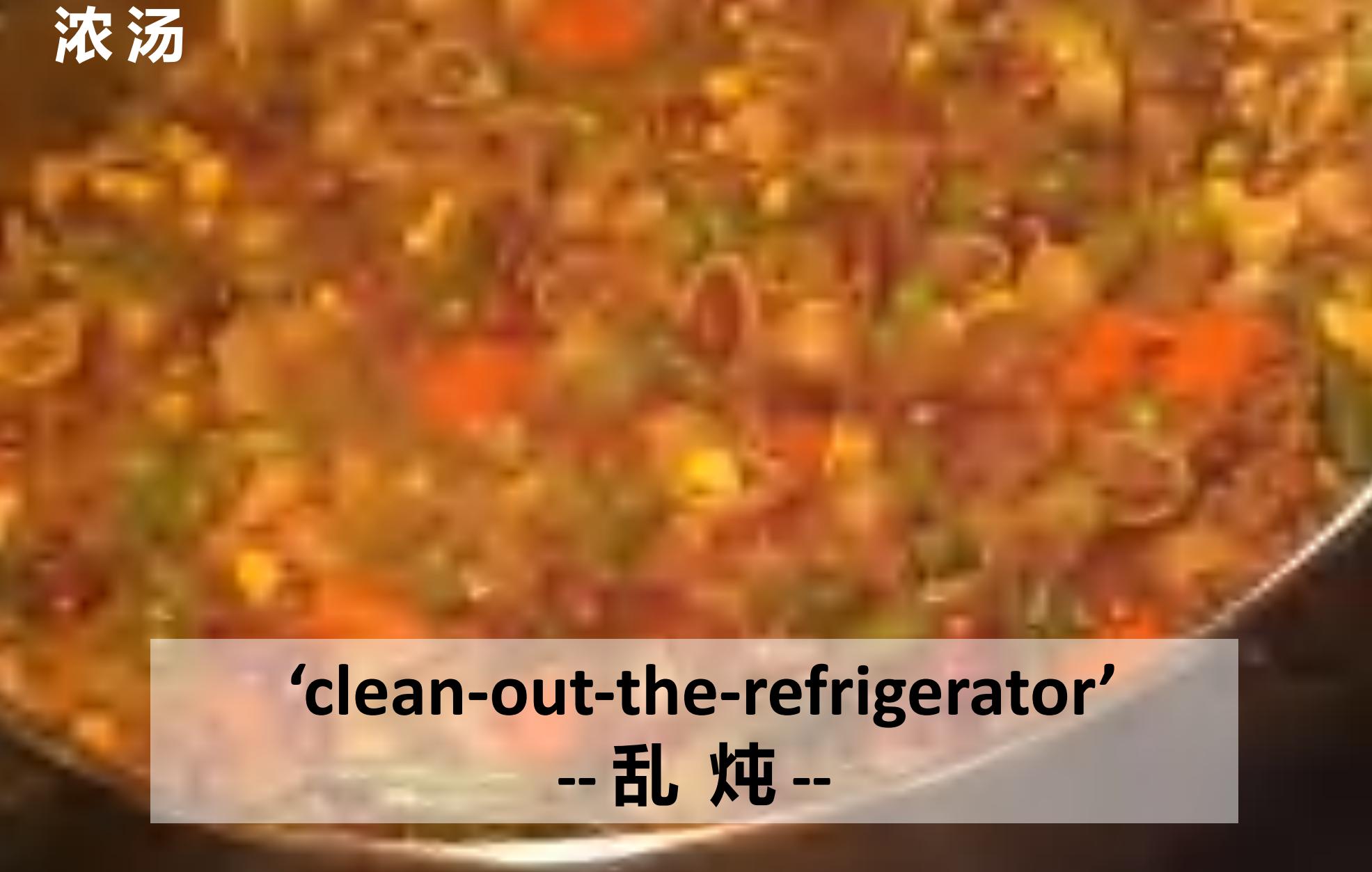
地面沉降  
地下水开采  
削山造城  
煤矿开采



地震震损

# Slumgullion

浓汤



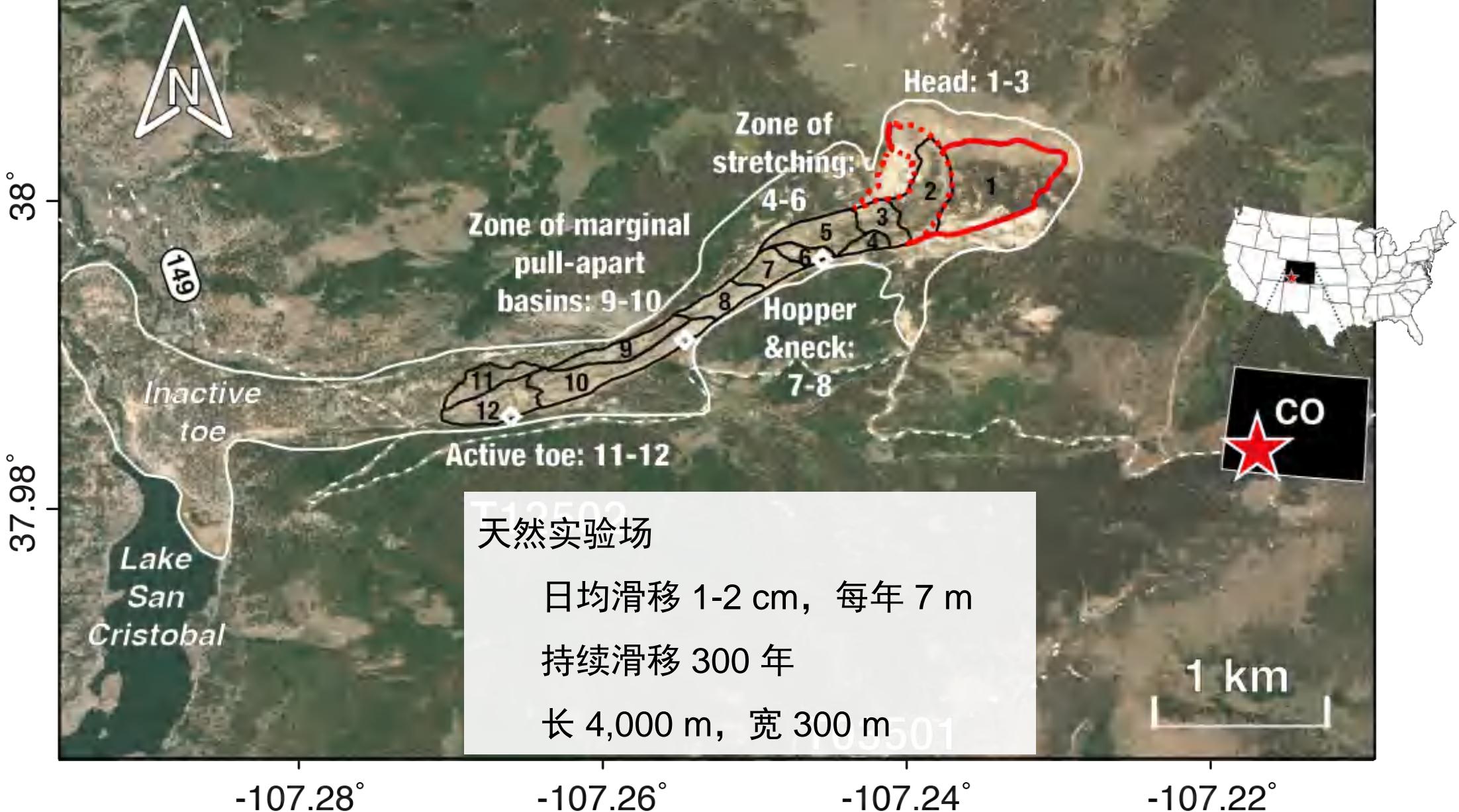
‘clean-out-the-refrigerator’  
-- 乱 炖 --

科罗拉多州  
Slumgullion  
滑坡趾



Cannibal Plateau

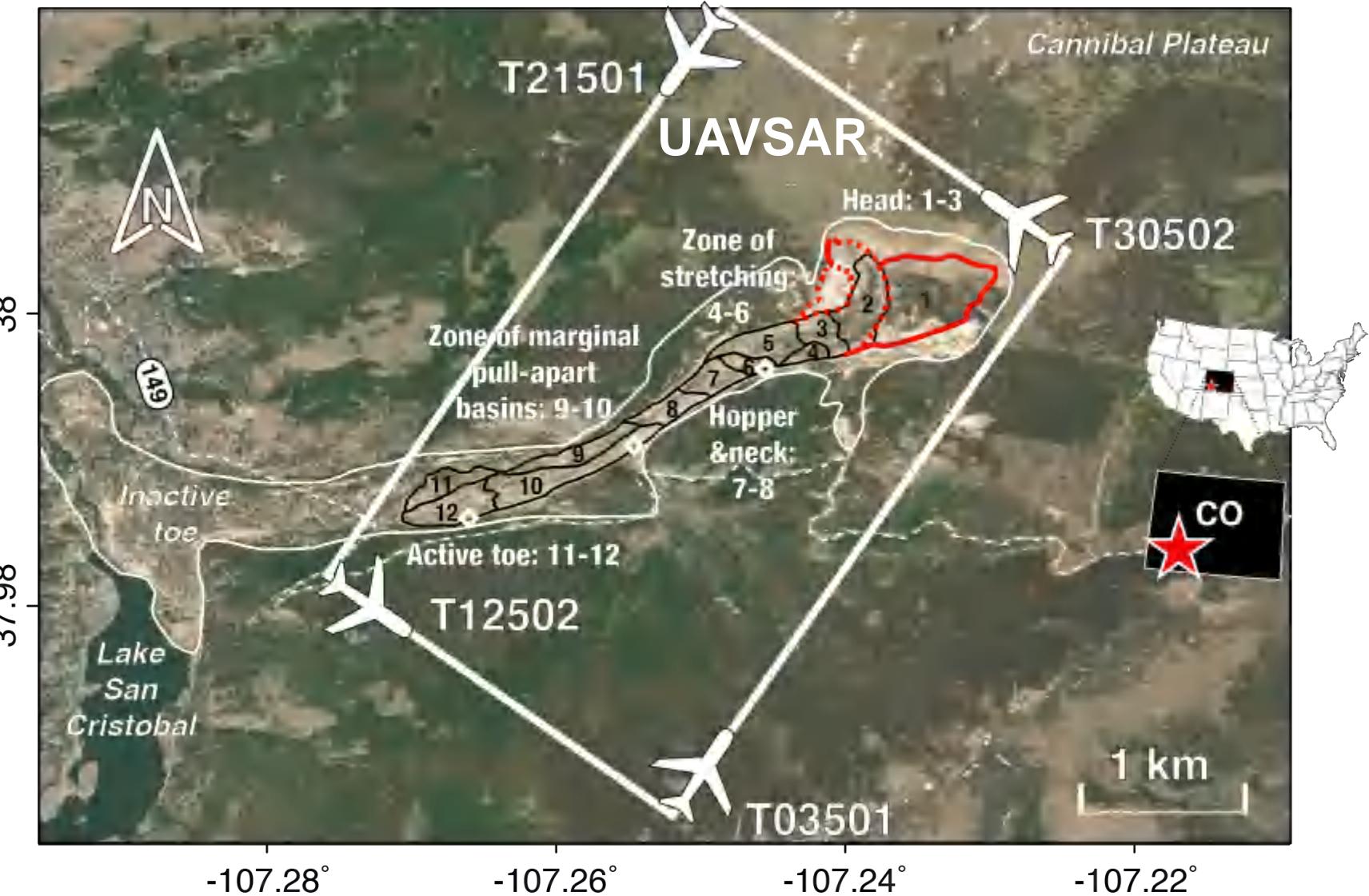
# 科罗拉多州 Slumgullion 滑坡



# 科罗拉多州 Slumgullion 滑坡

## 多源数据集

- 机载 UAVSAR (L-band)  
NASA | JPL; 2011-2018

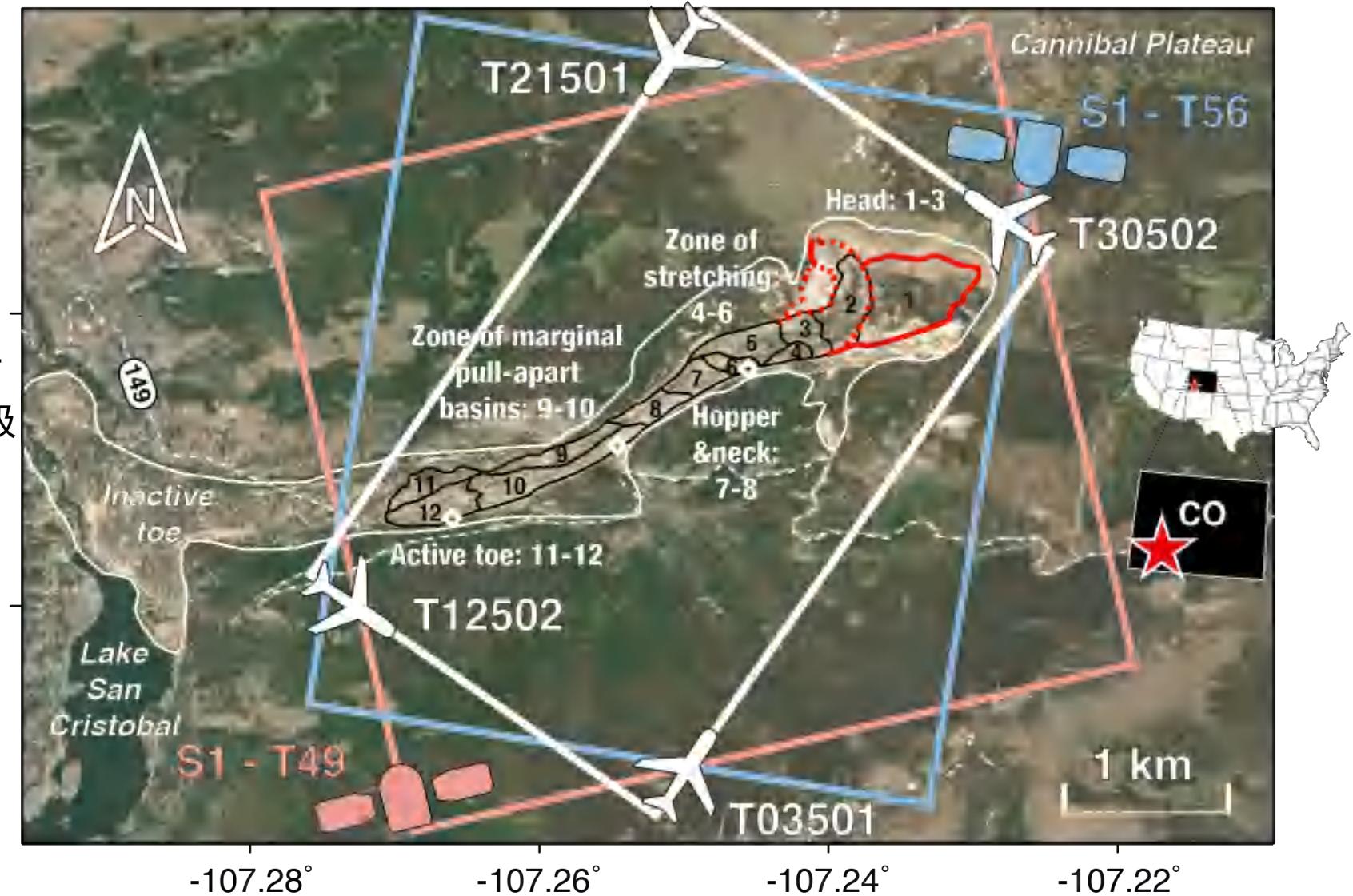


# 科罗拉多州 Slumgullion 滑坡

## 多源数据集

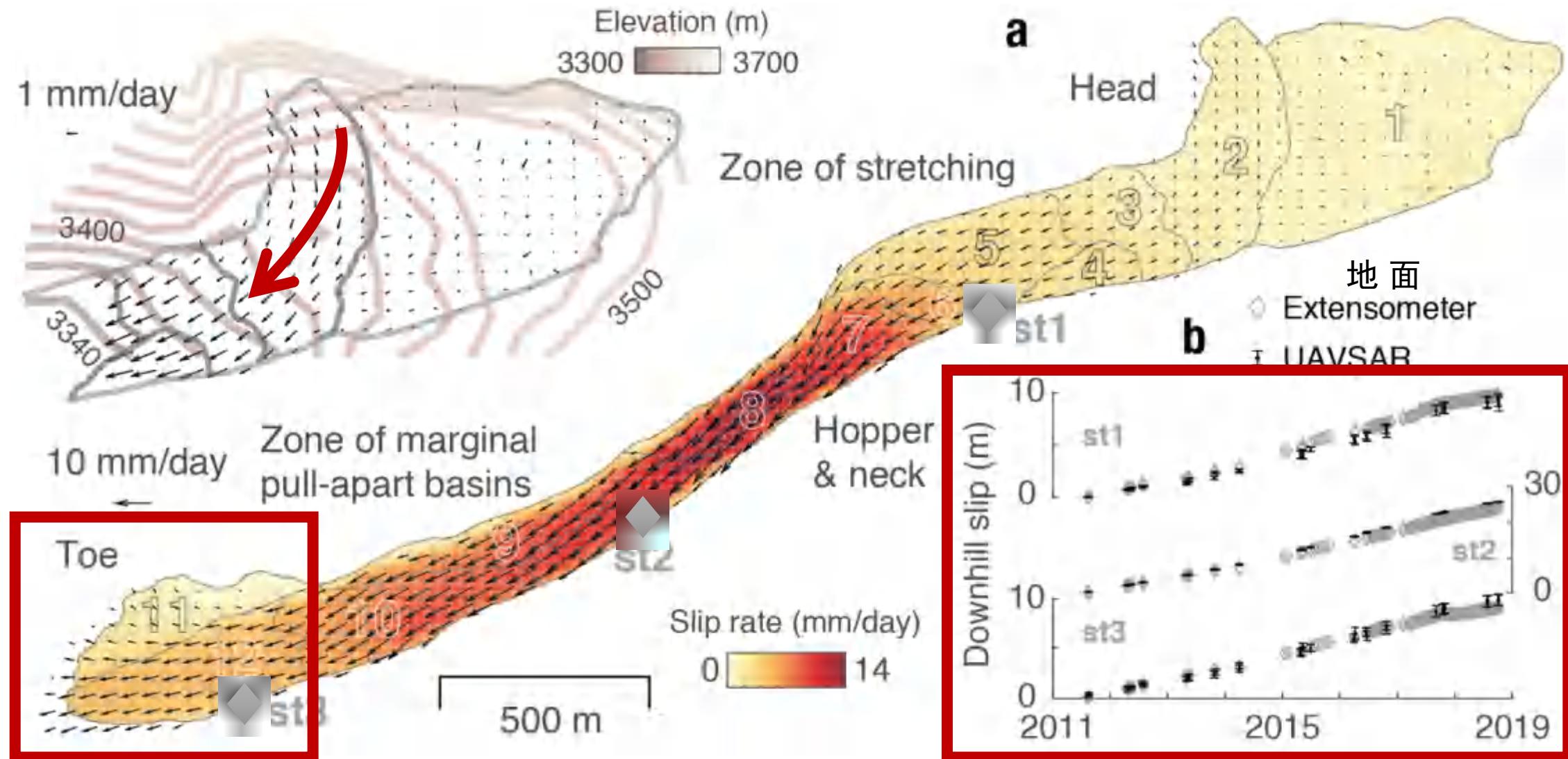
- 机载 UAVSAR (L-band)  
NASA | JPL; 2011-2018
- 星载 Sentinel-1 (C-band)  
ESA; 2017-2018
- 干涉测量InSAR + 像素偏移追踪POT  
1k+ 数据对, 超过过去研究2个数量级
- 实测大地测量 + 水文气象资料  
Extensometers Piezometer  
Inclinometers Precipitation gauge

Unprecedented data collection!!



# 科罗拉多州 Slumgullion 滑坡

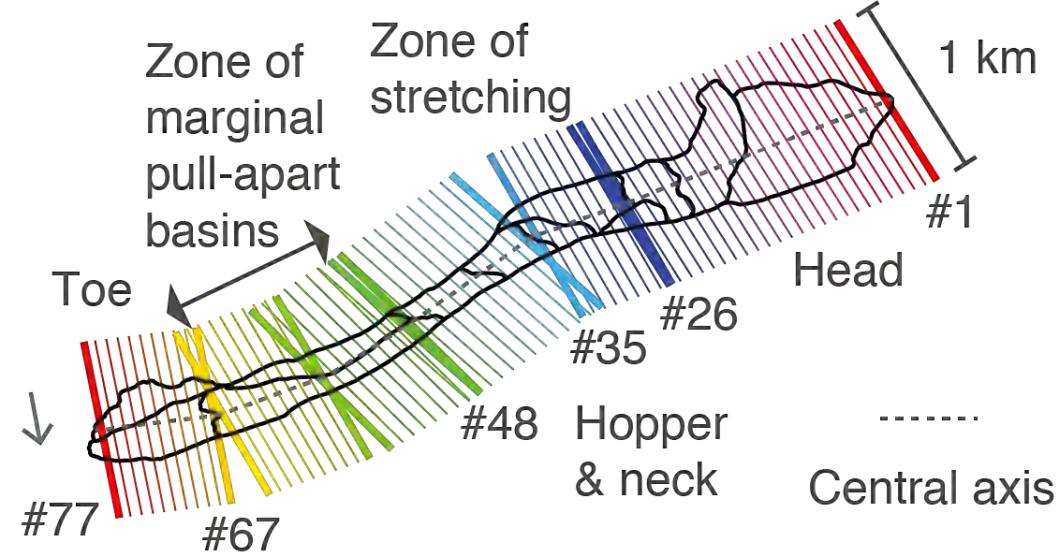
- 集成 InSAR + POT 技术获取高精度形变细节



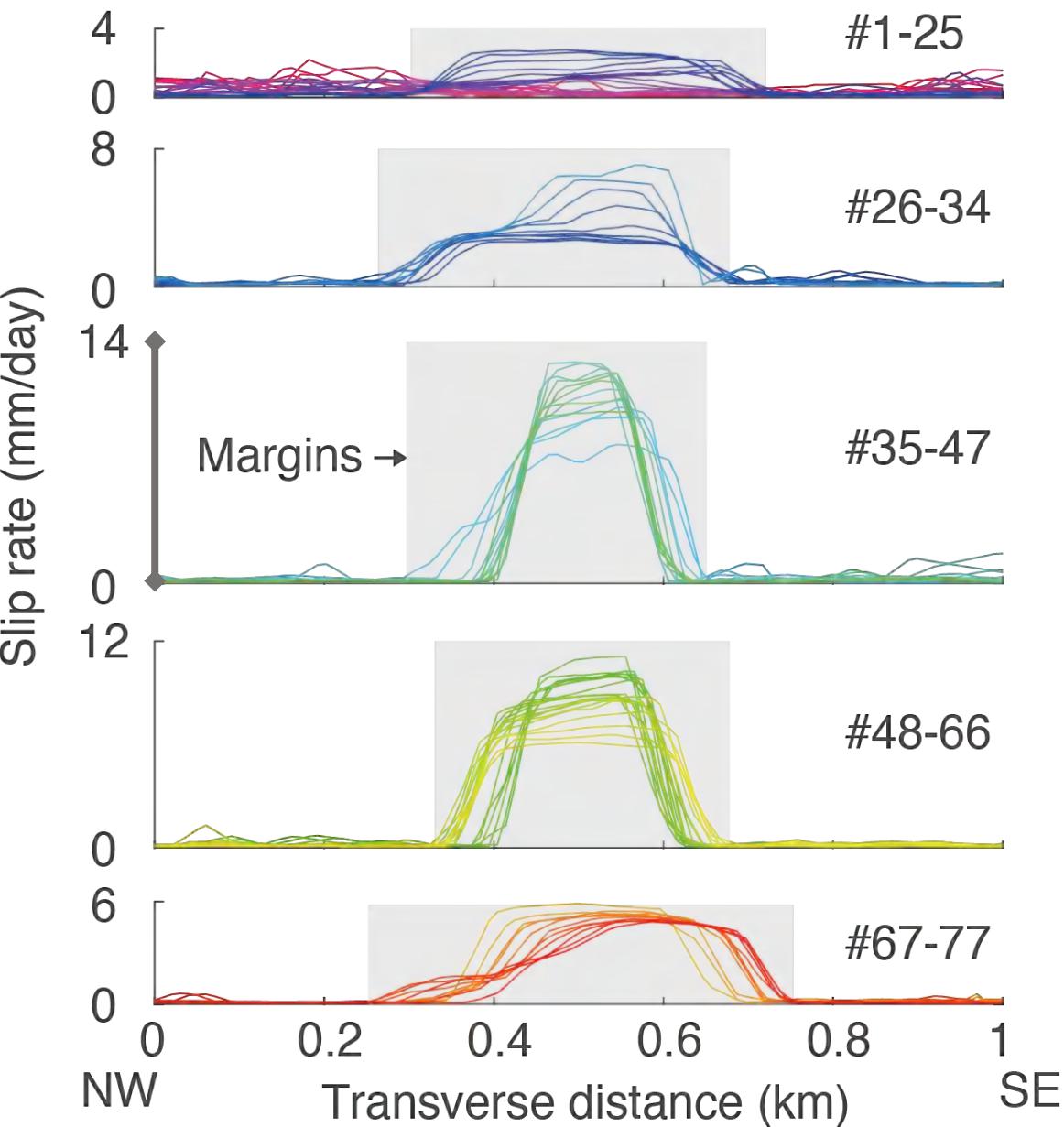
# 科罗拉多州 Slumgullion 滑坡

- 滑坡横轴剖线的表面径向流速

## Transverse profiles

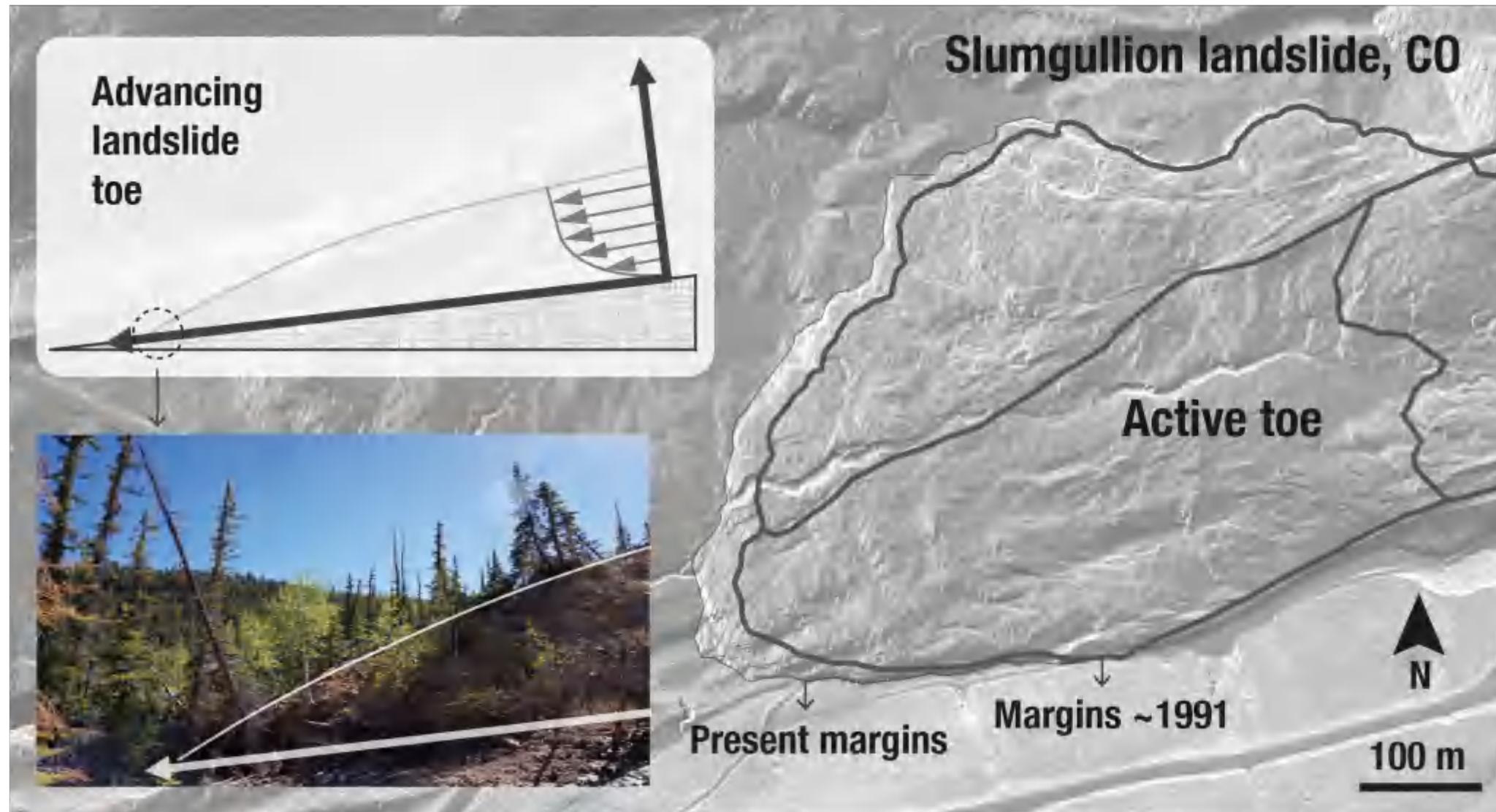


## Longitudinal surface velocity

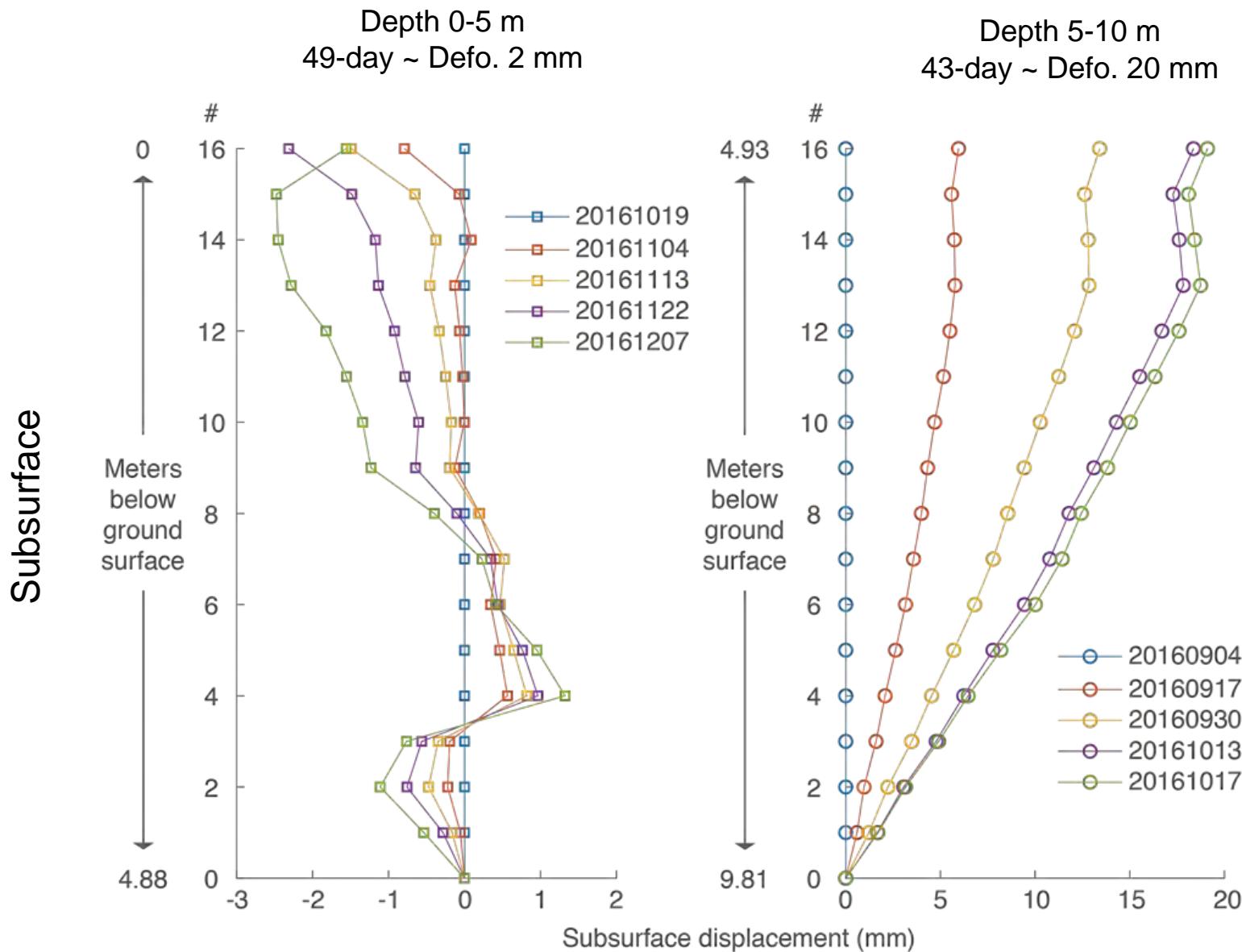


# 科罗拉多州 Slumgullion 滑坡

非牛顿流体运动

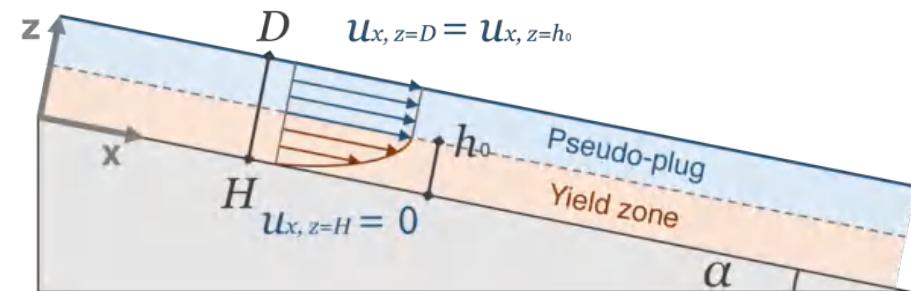


# 科罗拉多州 Slumgullion 滑坡



同期该地地表相对于稳定区运动了  
600 mm >> 浅部20 mm

Shallow → Pseudo-plug  
Deep → Yield zone

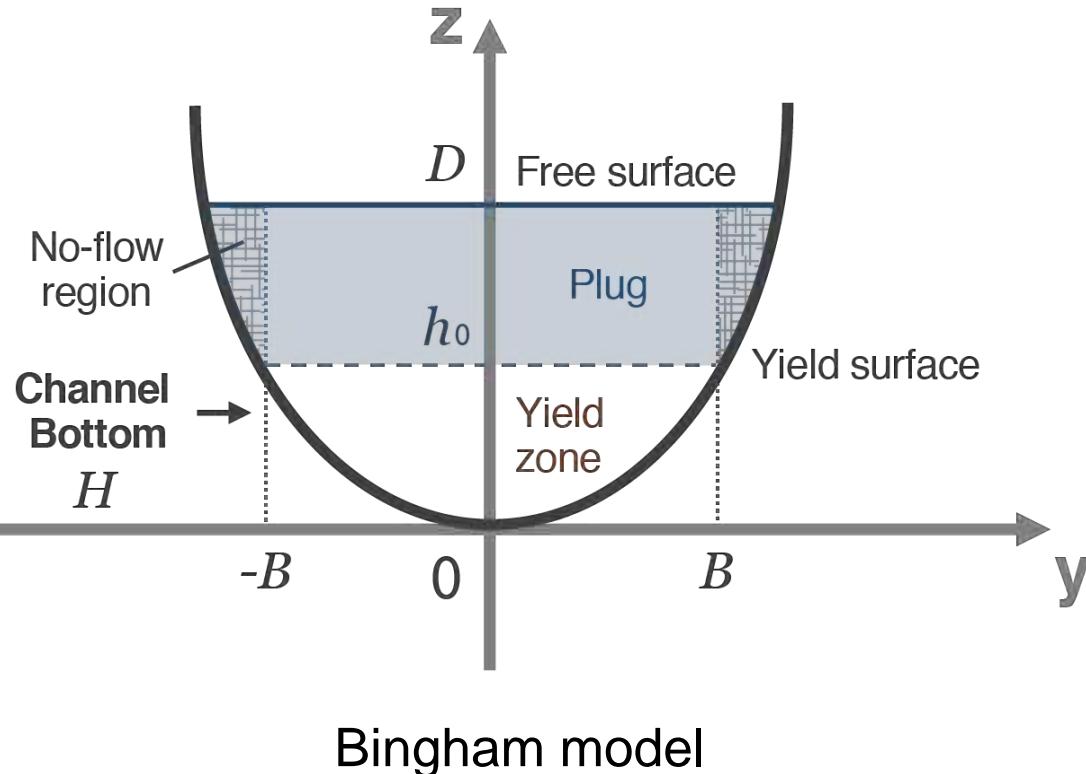


# 科罗拉多州 Slumgullion 滑坡

- 非牛顿流体模型选择

**a**

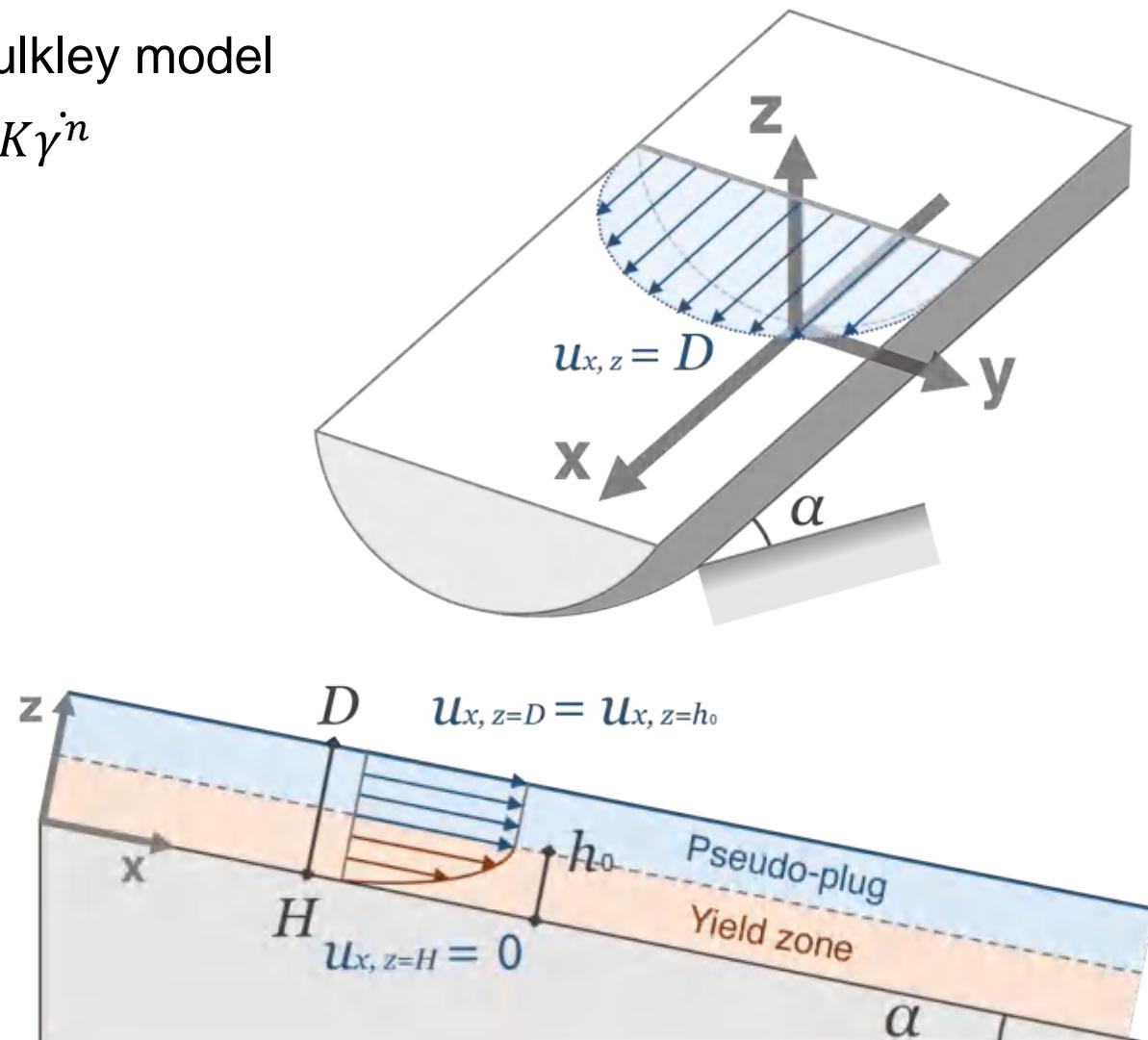
Mei and Yuhi (2001)



$$n = 1 \quad \text{Constant } \tau_c$$

The Herschel–Bulkley model

$$\tau = \tau_c + K\dot{\gamma}^n$$



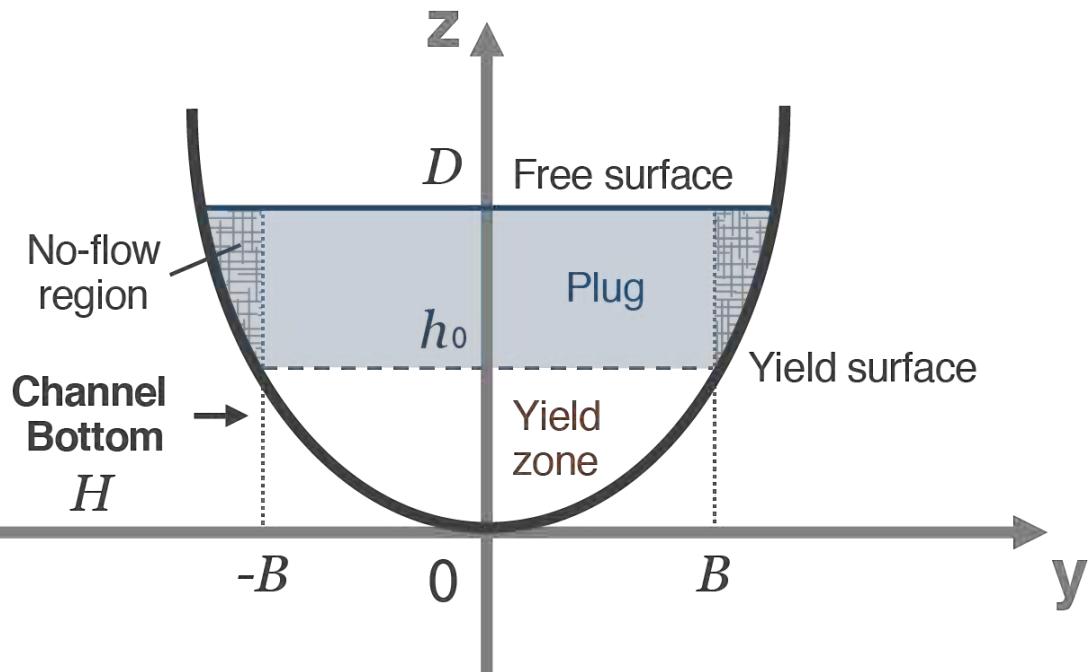
# 科罗拉多州 Slumgullion 滑坡

- 非牛顿流体模型选择

The Herschel–Bulkley model

a

Mei and Yuhi (2001)

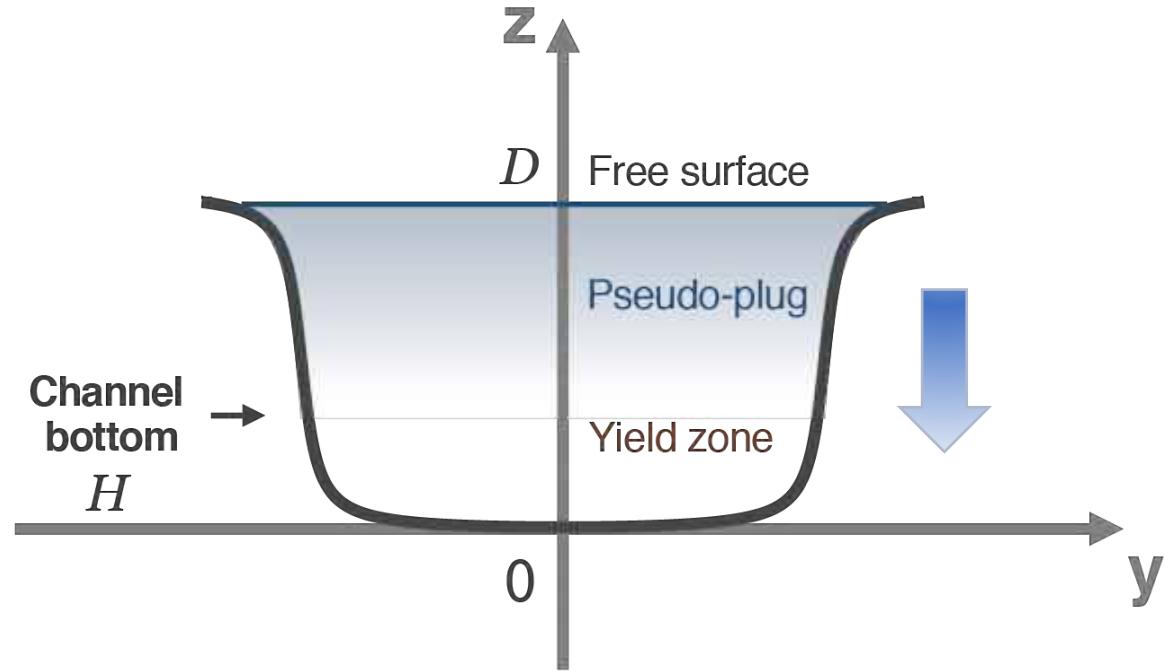


Bingham 模型

$$n = 1 \quad \tau_c \text{ 常数}$$

b

New sketch



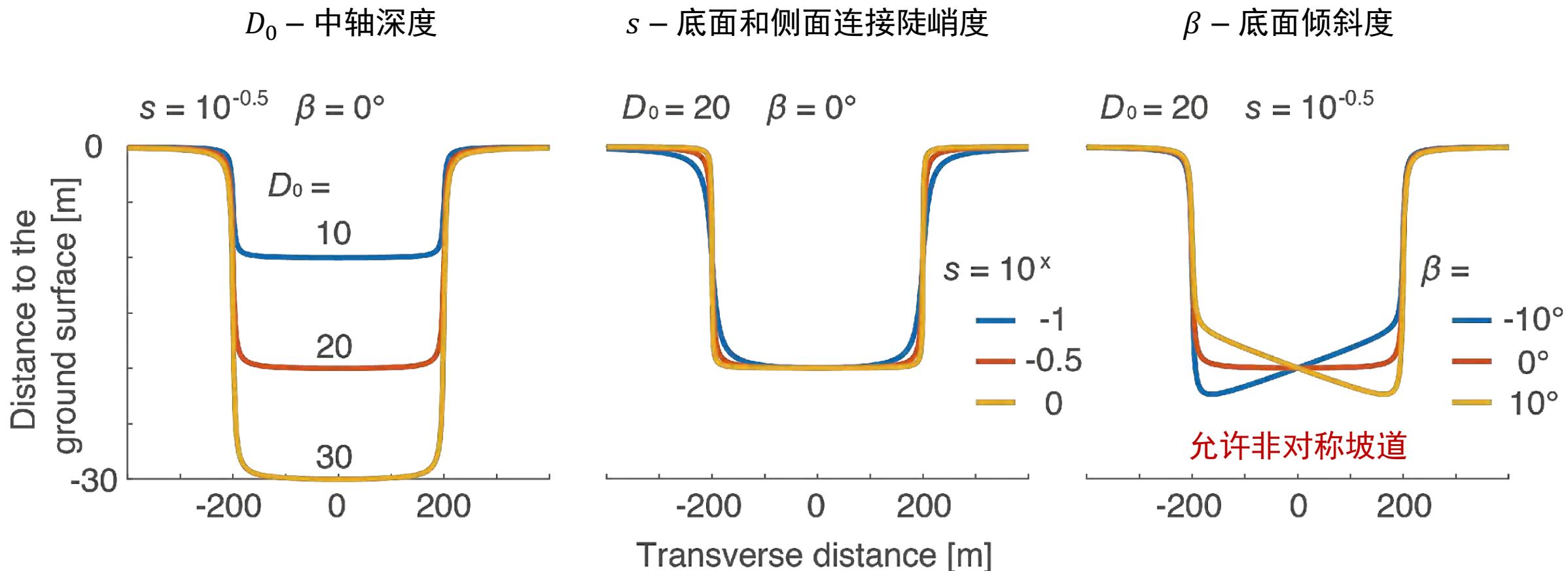
指数模型

$$\tau_c = 0$$

# 科罗拉多州 Slumgullion 滑坡

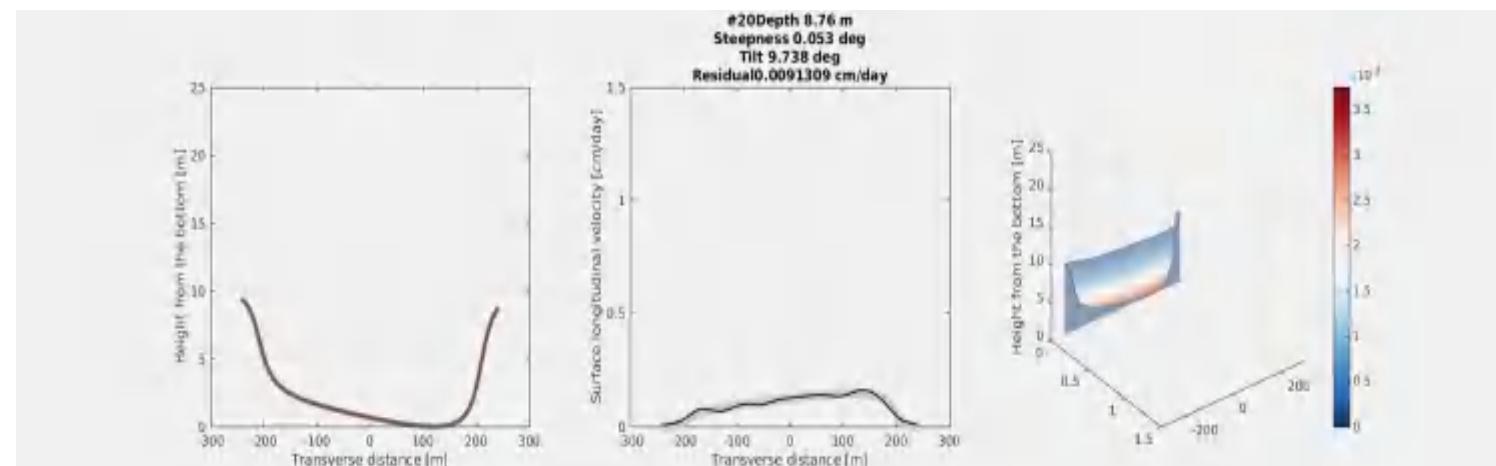
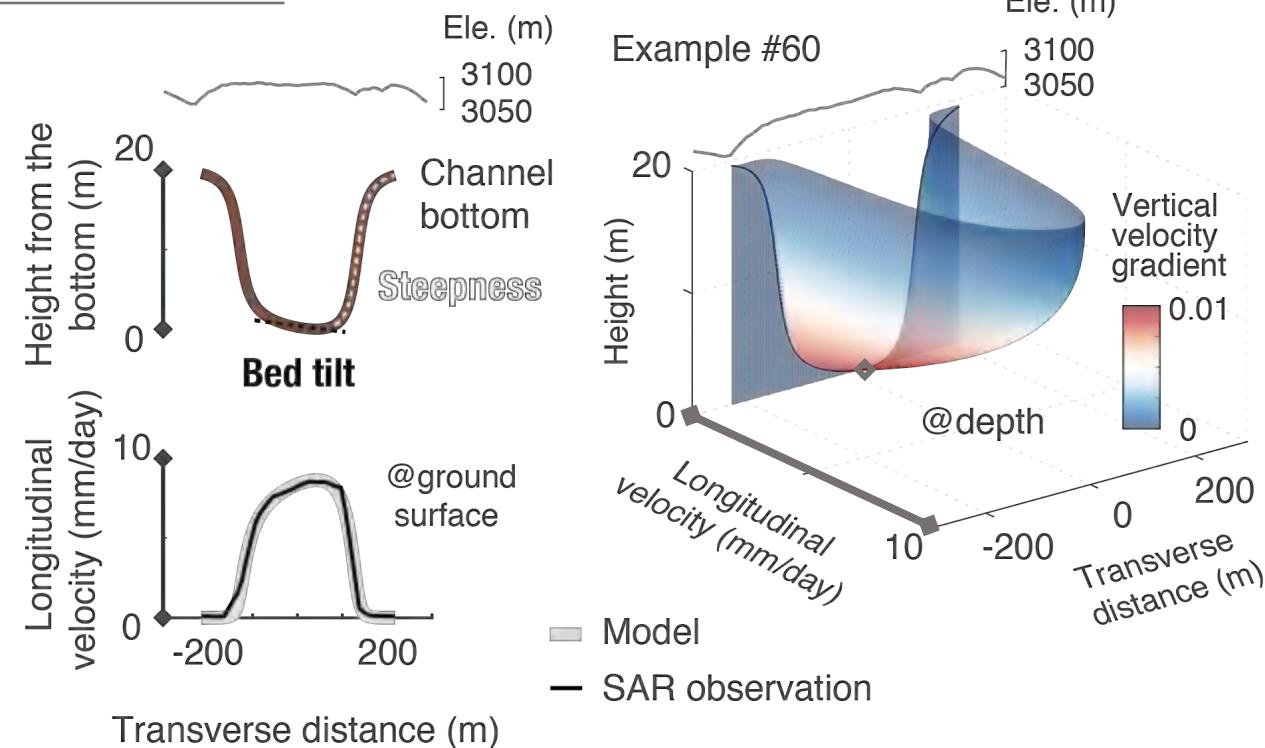
- 坡道几何形态

$$H = D_0 - \frac{\tan^{-1}\left(\left(y + \frac{L}{2}\right) \cdot s\right) + \tan^{-1}\left(\left(-y + \frac{L}{2}\right) \cdot s\right)}{2D_0 \cdot \tan^{-1}\left(\frac{L \cdot s}{2}\right)} \cdot \left(1 + \frac{2y \cdot \sin \beta}{L}\right)$$



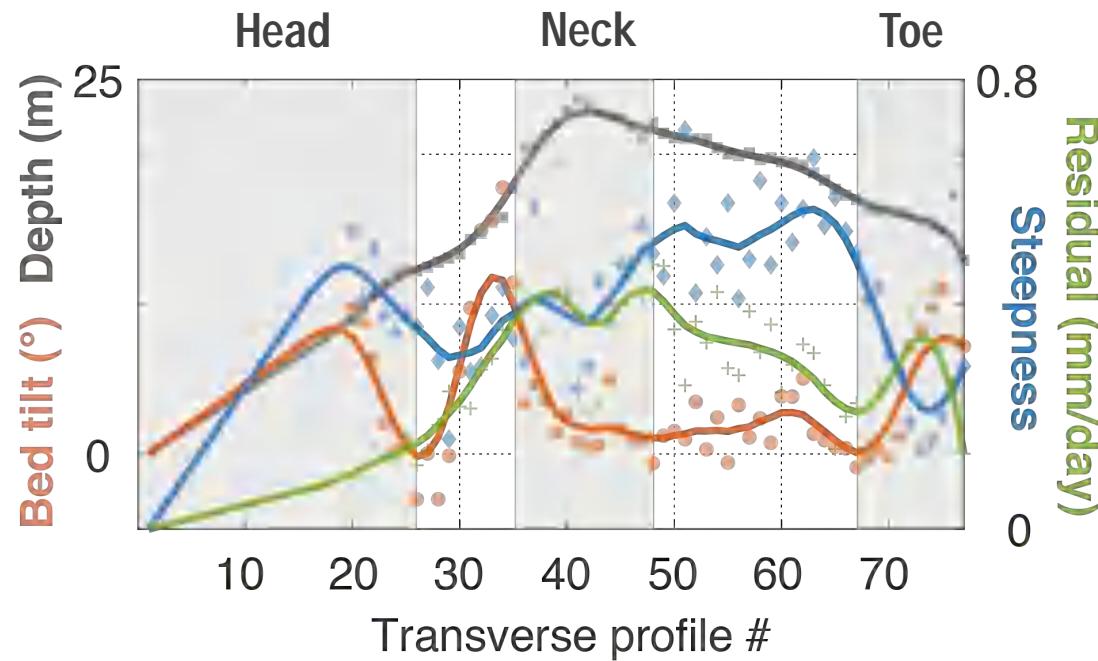
# 科罗拉多州 Slumgullion 滑坡

- 反演坡道几何形态  
地表地下径流速

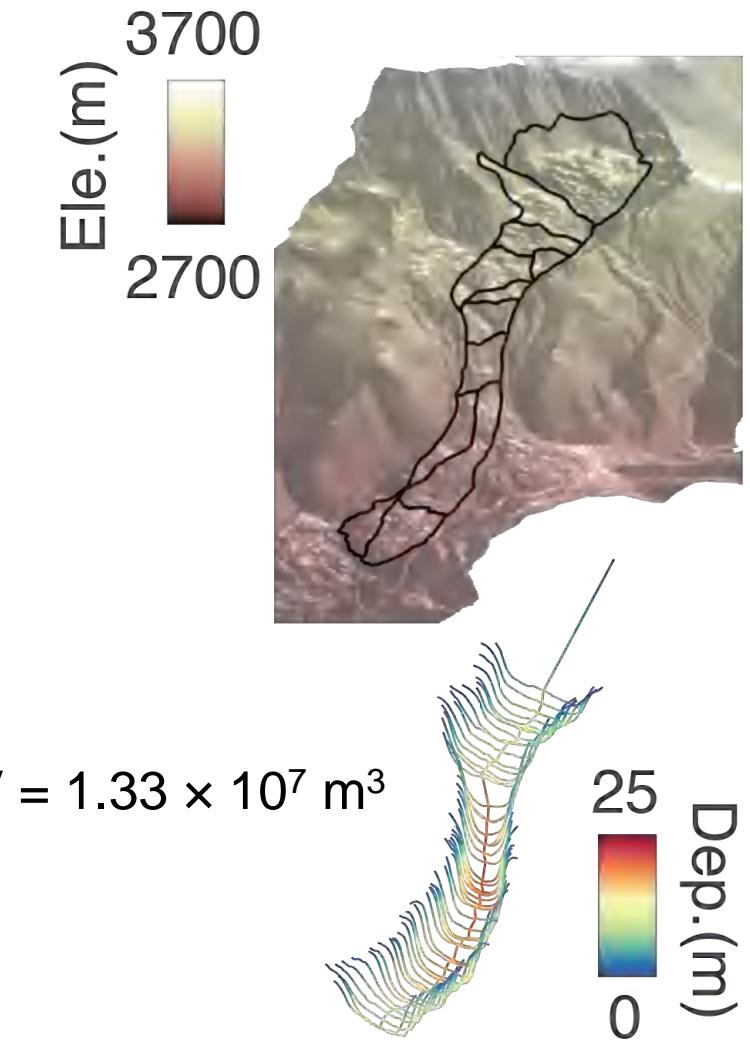
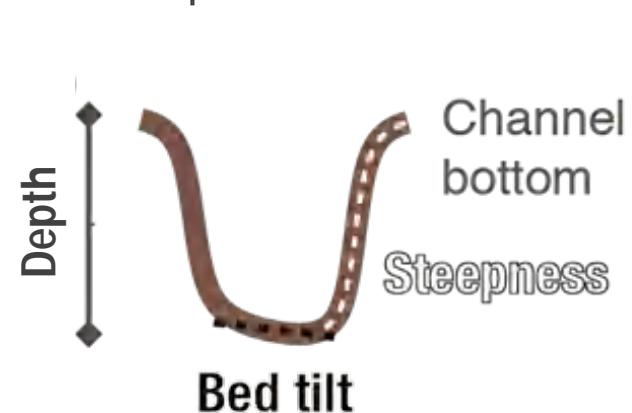
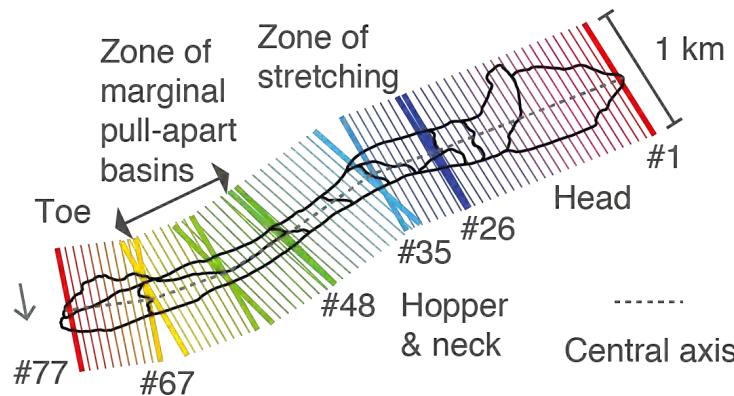


# 科罗拉多州 Slumgullion 滑坡

- 滑坡坡道几何形态



Transverse profiles



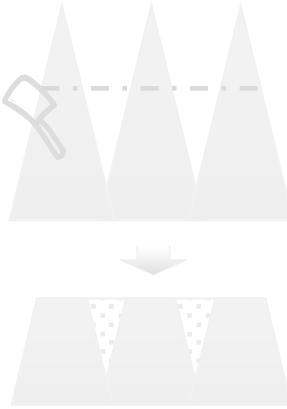


## 山体滑坡

粘塑性滑坡

水电站边坡

热融滑塌陷



## 地面沉降

地下水开采

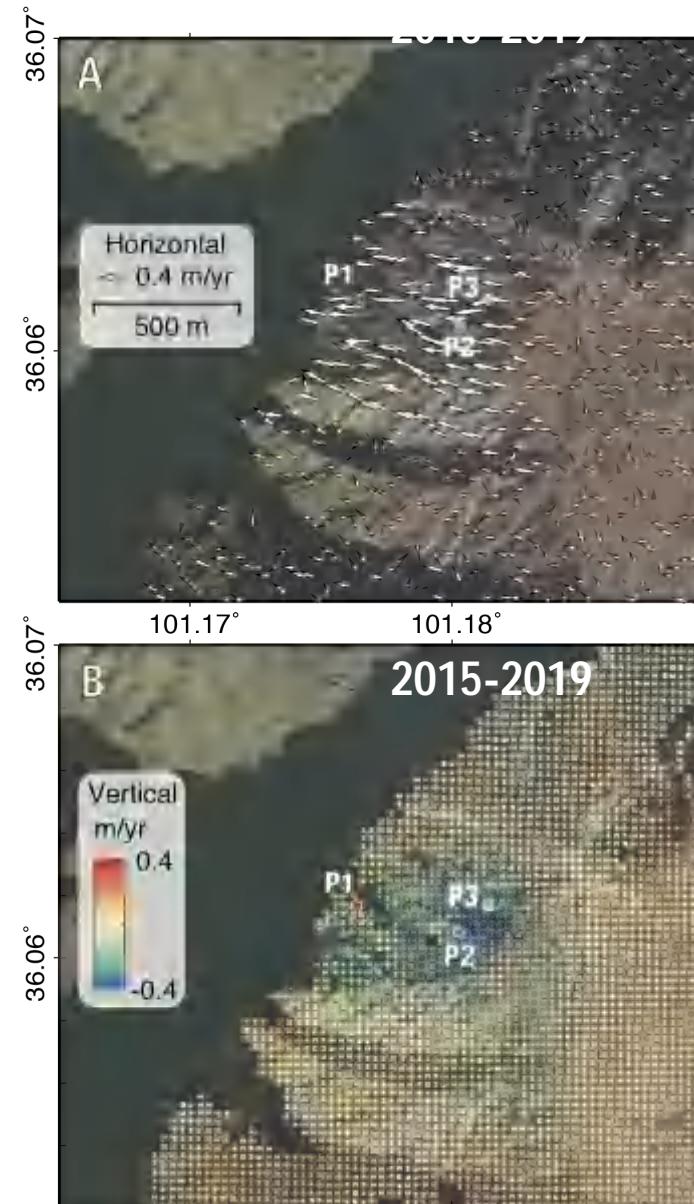
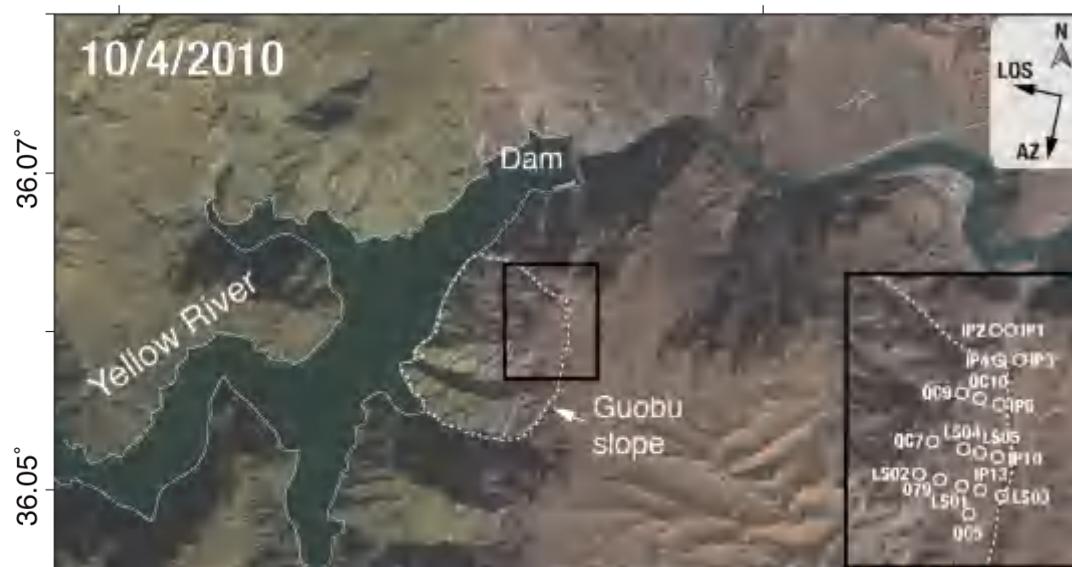
削山造城

煤矿开采



## 地震震损

# 青海省拉西瓦水电站



蓄水水位上涨

2009.3 首次蓄水  
2250 → 2340 m

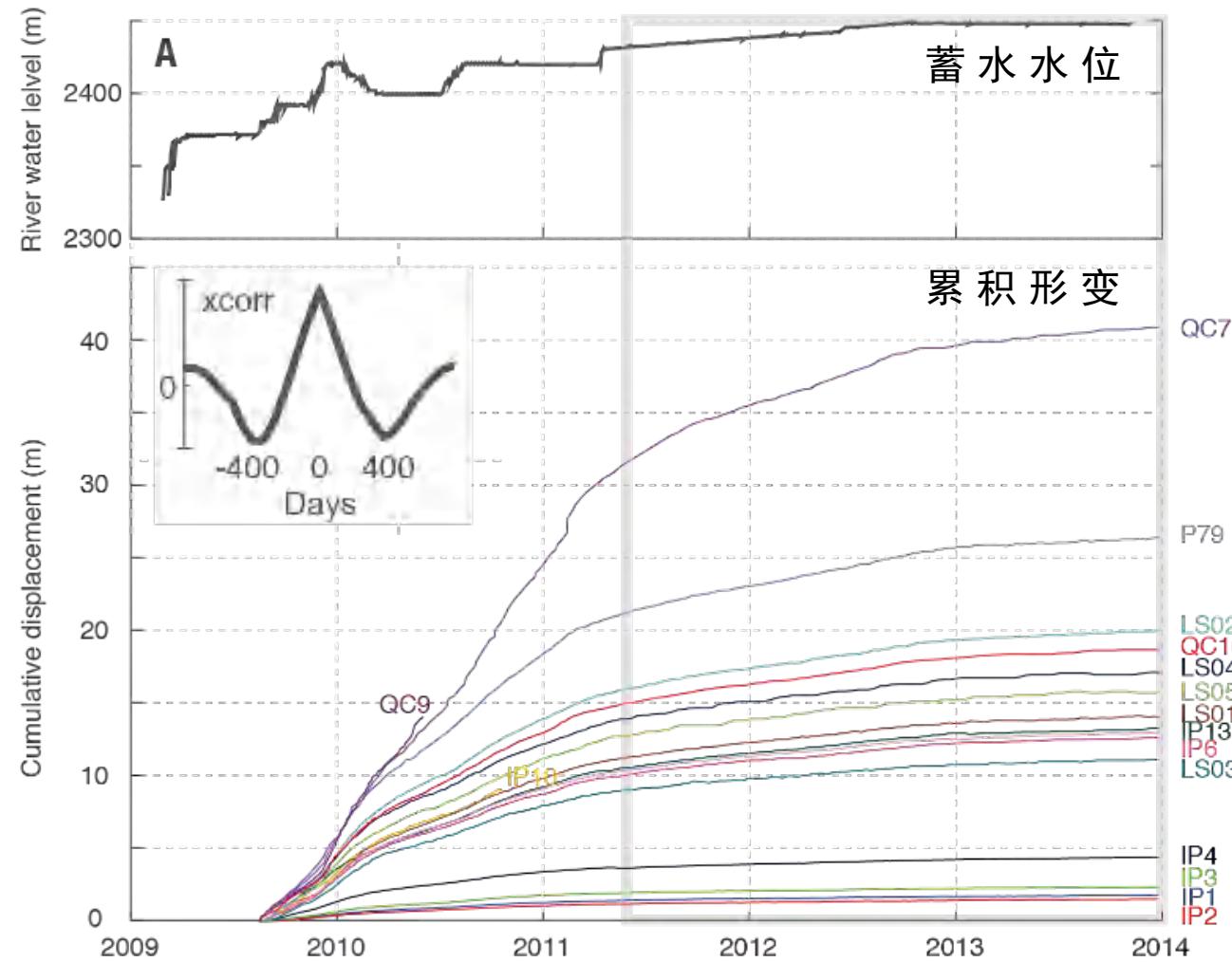
水位稳定  
2015.10: 2452 m

目前仍活动状态  
垂直向: 0.4 m/yr  
水平向: 0.7 m/yr

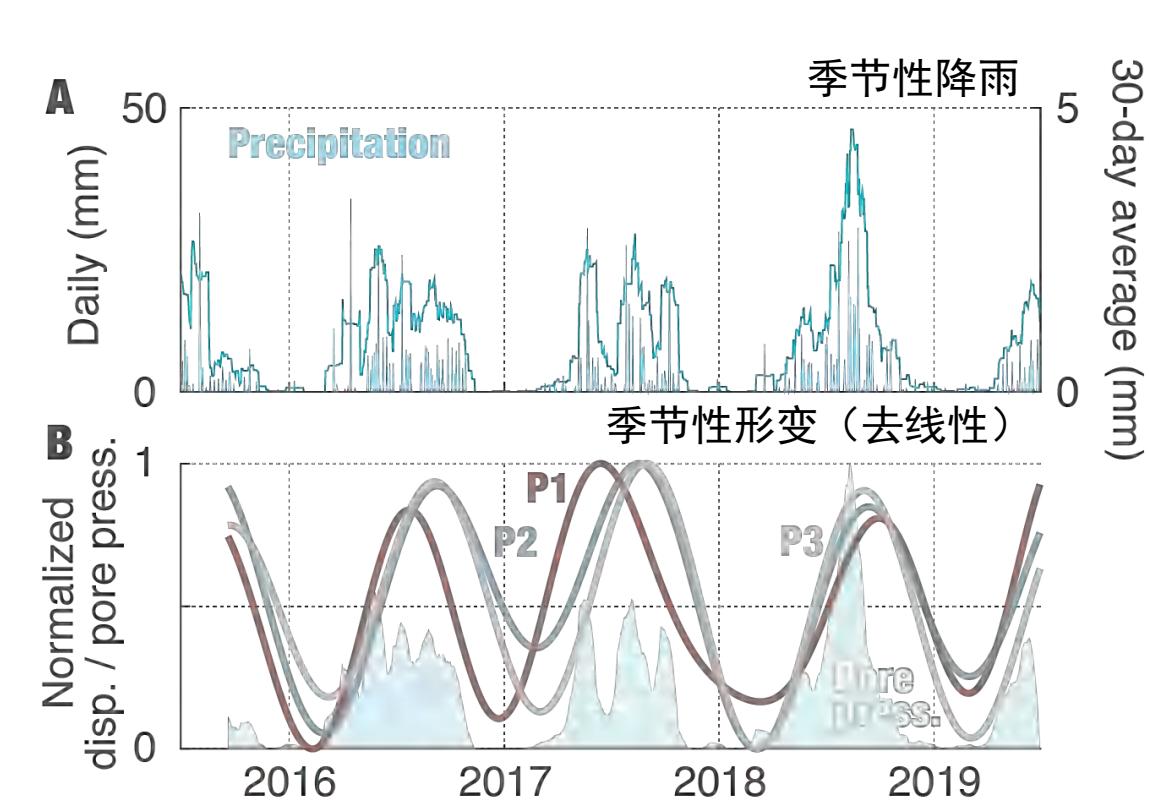
# 青海省拉西瓦水电站

## 滑坡运动控制因素改变

2015年前：水位控制



2015年后：季节性降雨控制



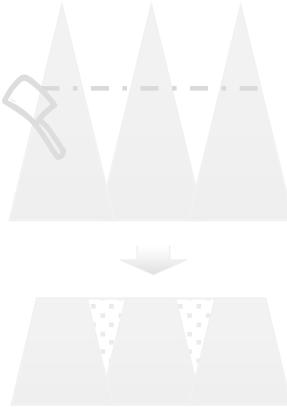


## 山体滑坡

粘塑性滑坡

水电站边坡

热融滑塌陷



## 地面沉降

地下水开采

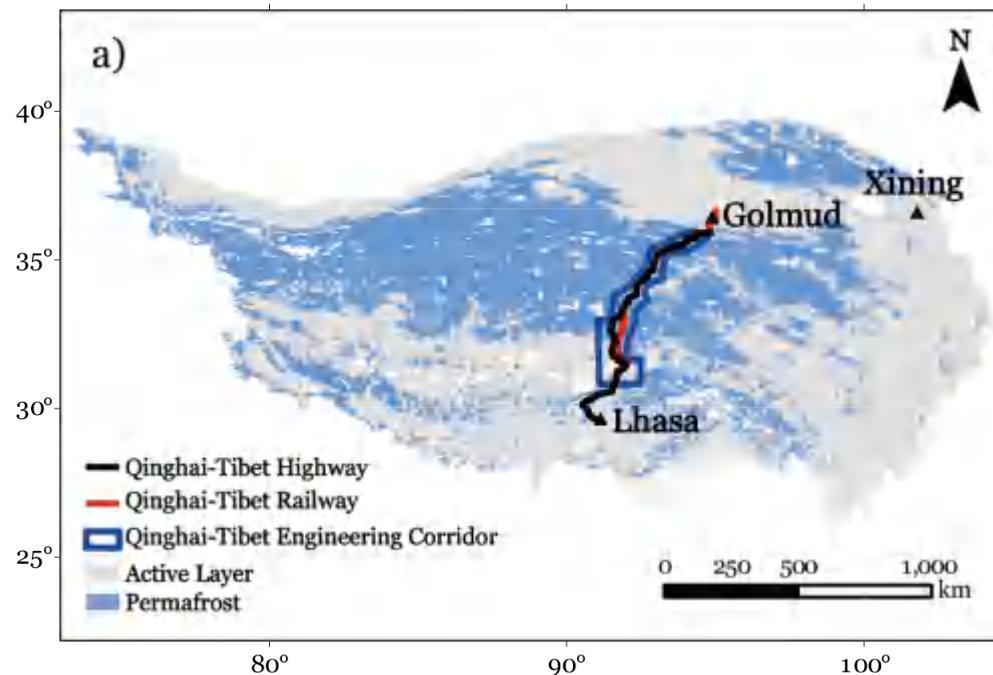
削山造城

煤矿开采



## 地震震损

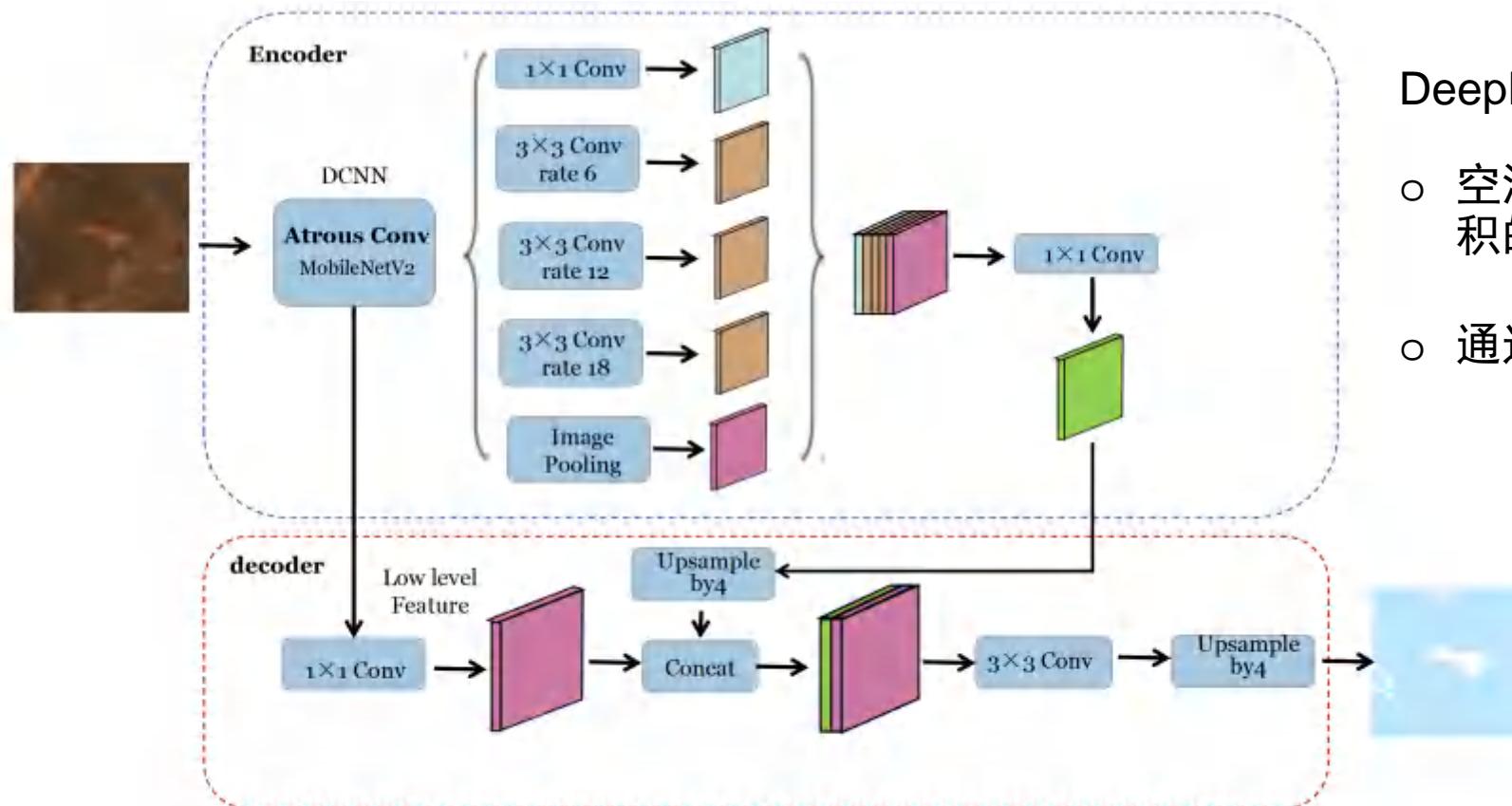
# 青藏高原北麓河地区热融滑塌多年期编目



- 青藏工程走廊遭受融沉冻胀、地基病变的危险
- 热喀斯特地貌: 热融滑塌
  - 与背景光谱差异明显
  - 沿着顶墙的方向后退



# 青藏高原北麓河地区热融滑塌多年期编目



DeepLabv3+ Semantic Segmentation Model

- 空洞卷积的深度卷积神经网络，提高了卷积的感受野，实现了精度和速度的平衡
- 通过迭代降低目标损失函数的值

# 青藏高原北麓河地区热融滑塌多年期编目

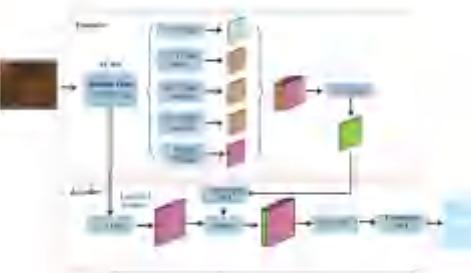
- 边界提取
- 负样本



Esri Imagery

Google Earth

802  
positive  
examples



true  
positive  
examples

false  
positive

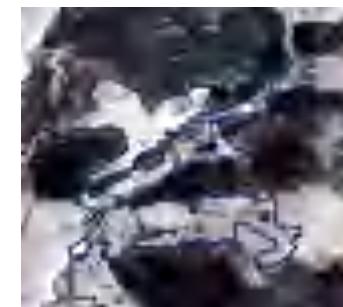
Snow



Cloud



Bare land



Mound

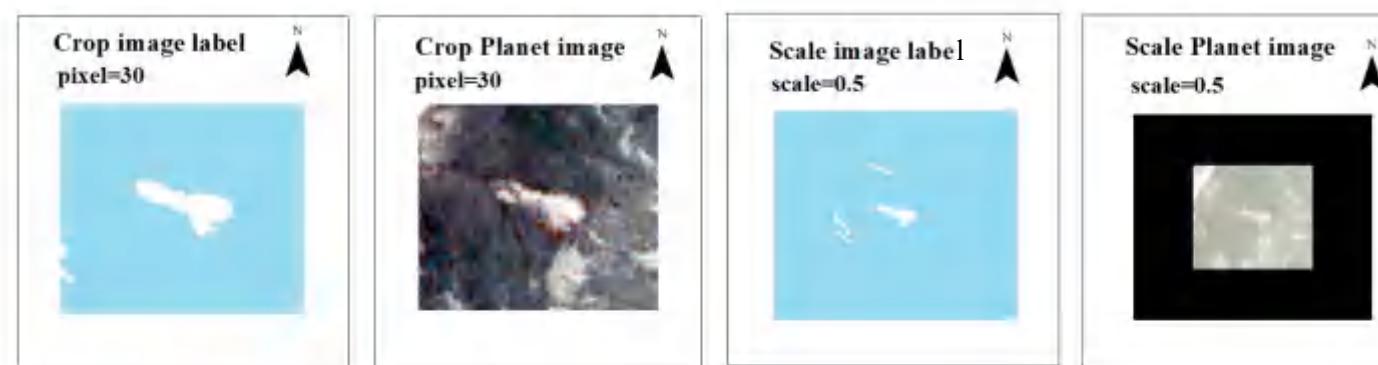
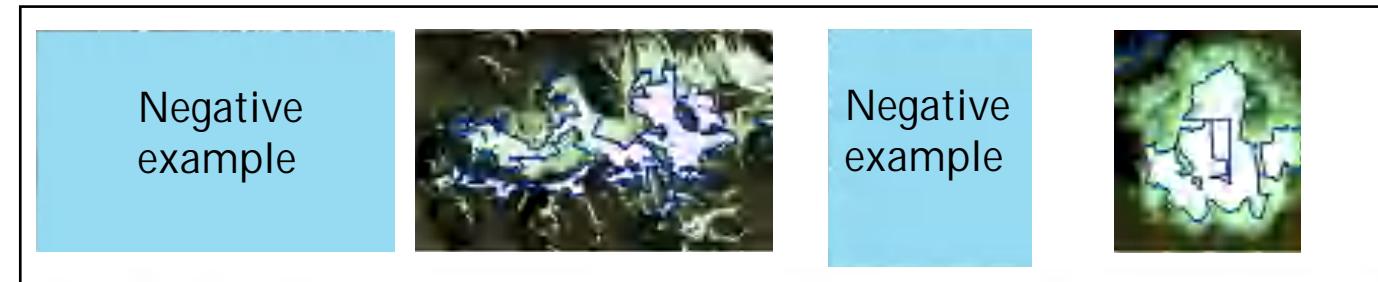


Sand dune

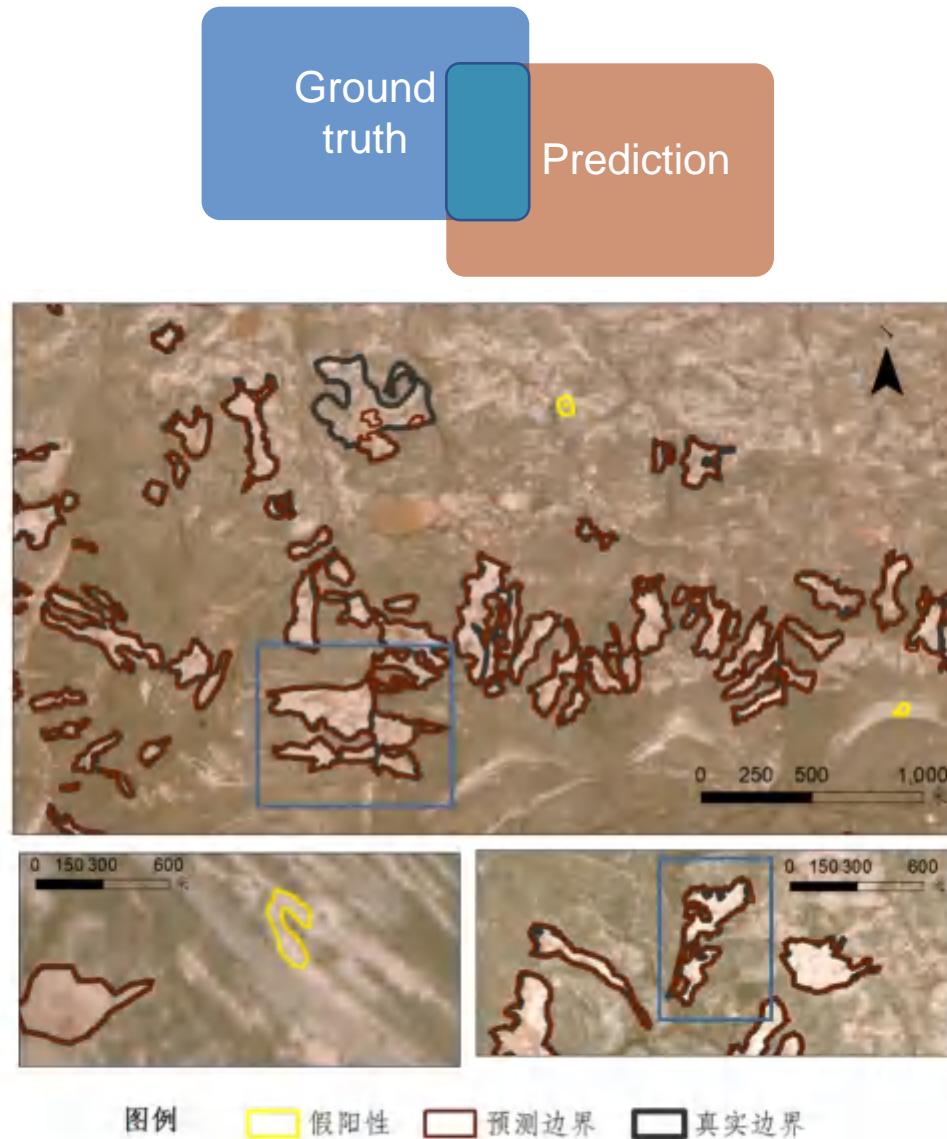


# 青藏高原北麓河地区热融滑塌多年期编目

- 缓冲区 (300 m)
- 栅格化
- 数据增强



# 青藏高原北麓河地区热融滑塌多年期编目



$$\text{IOU}(A,B)=\text{area}(A \cap B)/\text{area}(A \cup B)$$

TP       $\text{IOU} > \text{threshold}$

FP       $\text{IOU} < \text{threshold}$

召回率     $\text{Recall} = (\text{TP})/(\text{TP}+\text{FN})$

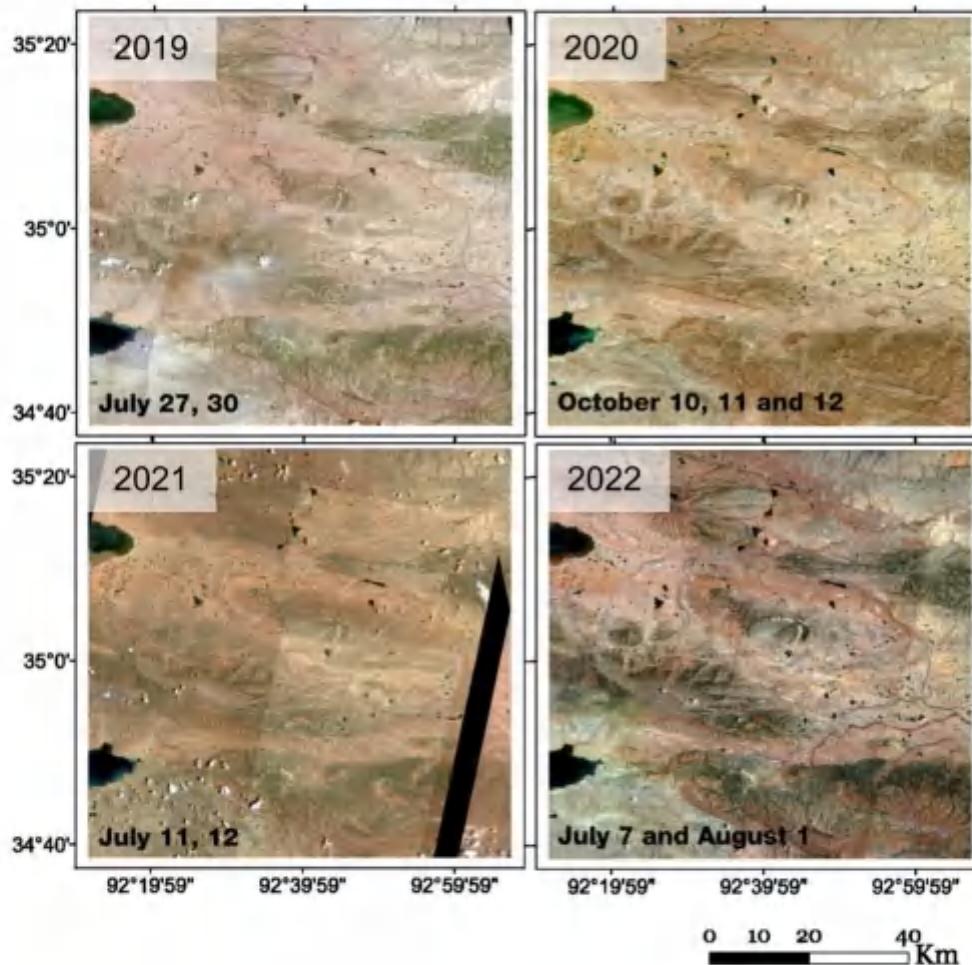
准确率     $\text{Precision} = (\text{TP})/(\text{TP}+\text{FP})$

$$F = \frac{(1+\beta^2) \times \text{Recall} \times \text{Precision}}{\beta^2 \times \text{Recall} + \text{Precision}}$$

召回率的重要性高于准确率  
 $\beta = 3$

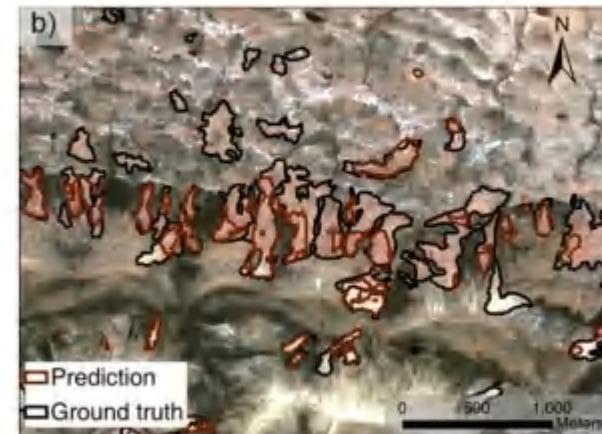
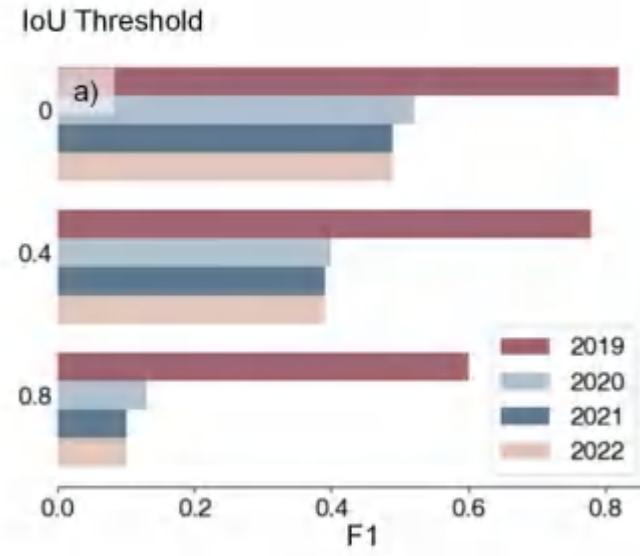
IOU threshold	0	0.2	0.	0.6	0.8
Recall	0.934	0.918	0.880	0.836	0.685
Precision	0.820	0.805	0.773	0.733	0.601
F1	0.829	0.815	0.782	0.742	0.608

# 青藏高原北麓河地区热融滑塌多年期编目



## ○ 域自适应方法 Domain adaption method

- 源域 Source domain (2019)
- 目标域 target domain (2020 | 2021 | 2022)



# 青藏高原北麓河地区热融滑塌多年期编目

## 领域自适应方法

- 微调 (Fine-tuning)

从目标年份中的地面真相数据中抽取5%、10%和20%的热融滑塌地面边界数据

- CycleGAN (Generative Adversarial Network)

易引入较多的假阳性

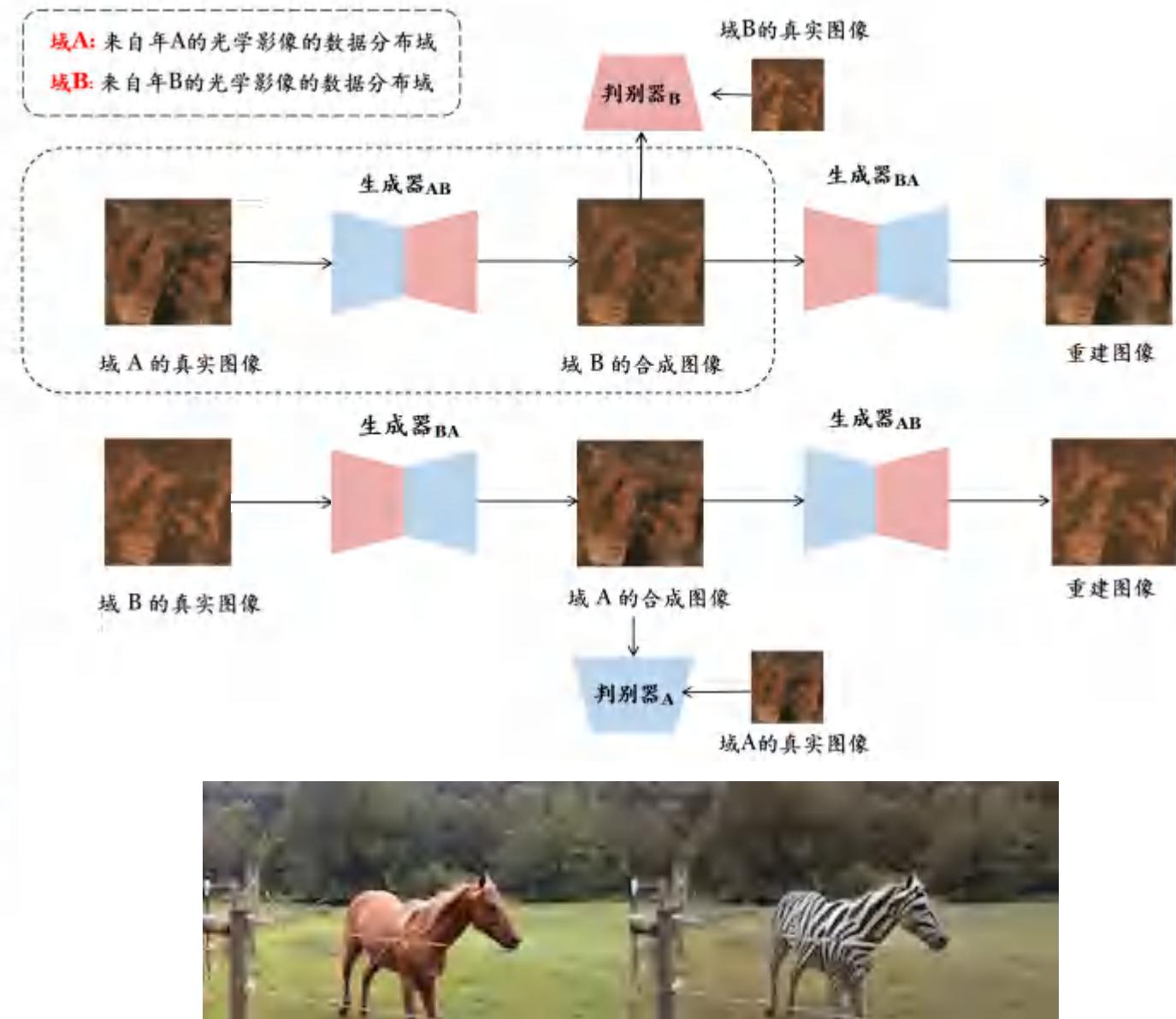
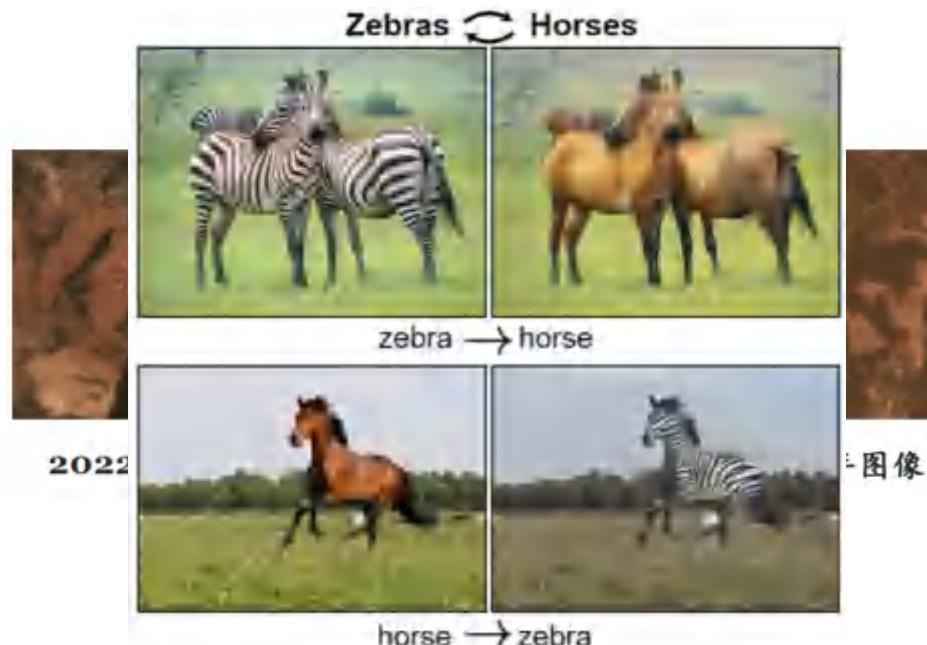
- 域对抗训练 DANN (Domain-Adversarial Training of Neural Networks)

梯度反转层 (Gradient reversal layer, GRL) + 损失函数

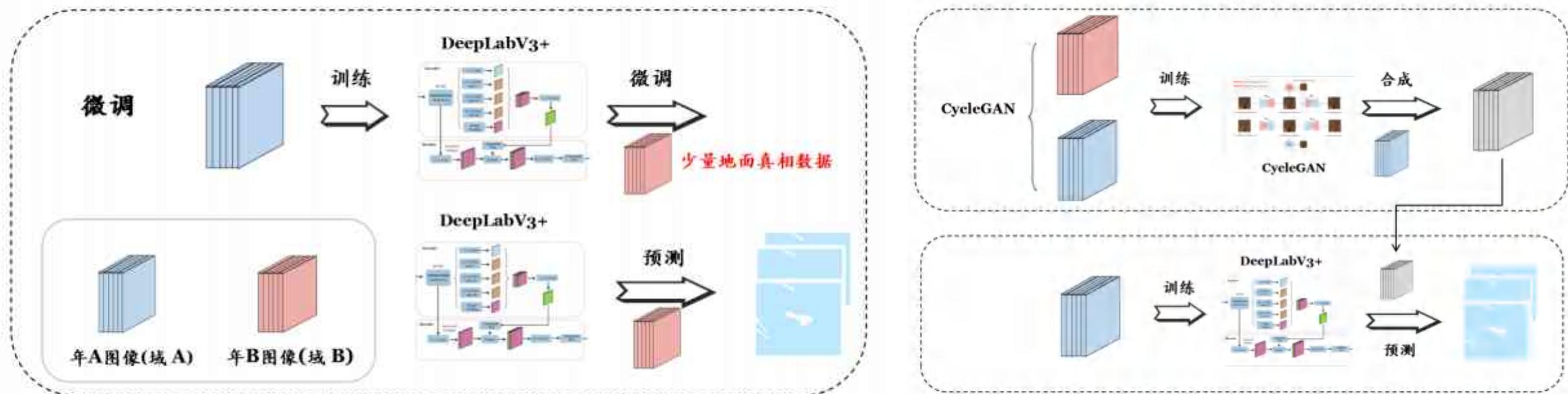
# 青藏高原北麓河地区热融滑塌多年期编目

## CycleGAN (Generative Adversarial Network)

- 生成对抗网络由生成器(Generator)和判别器(Discriminator)组成
- ✓ 生成器的目标是生成能够欺骗判别器的数据
- ✓ 判别器的目标是尽可能区分出真实数据和生成器生成的数据
- 引入循环一致性损失函数，实现自我监督机制



# 青藏高原北麓河地区热融滑塌多年期编目

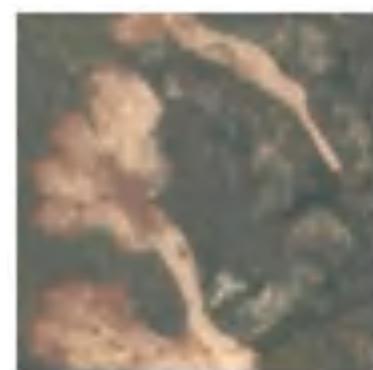


## 微调 Fine-tuning

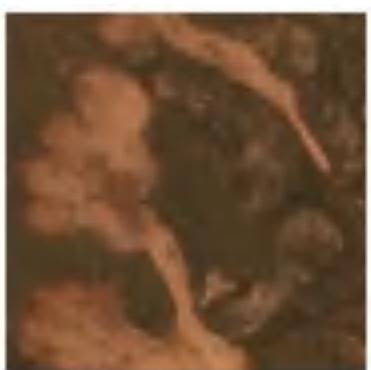
- 从目标年份中的地面真相数据中抽取5%、10%和20%的热融滑塌地面边界数据对模型进行微调，能有效提升其迁移性能。

## CycleGAN

- CycleGAN能够提高模型的时间泛化能力，但易引入较多的假阳性。



2022年图像

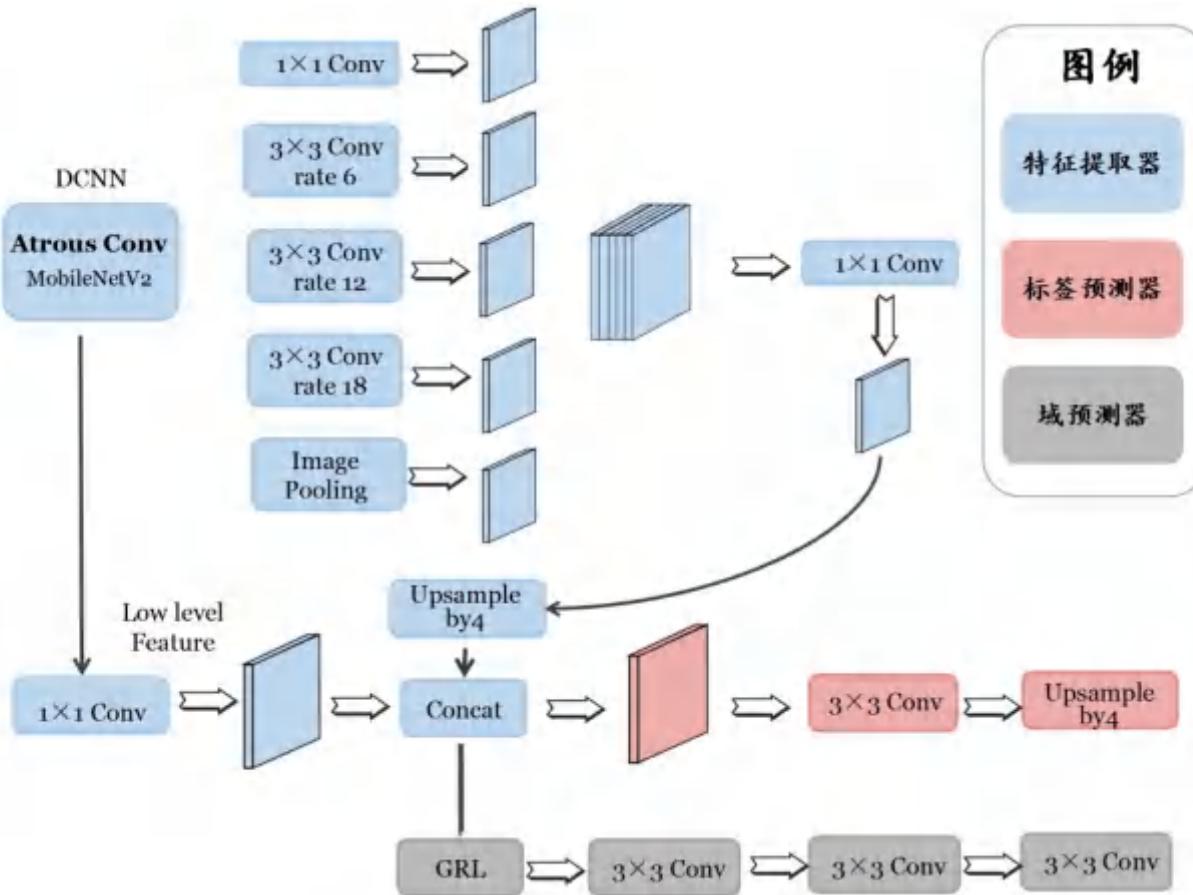


合成图像



2019年图像

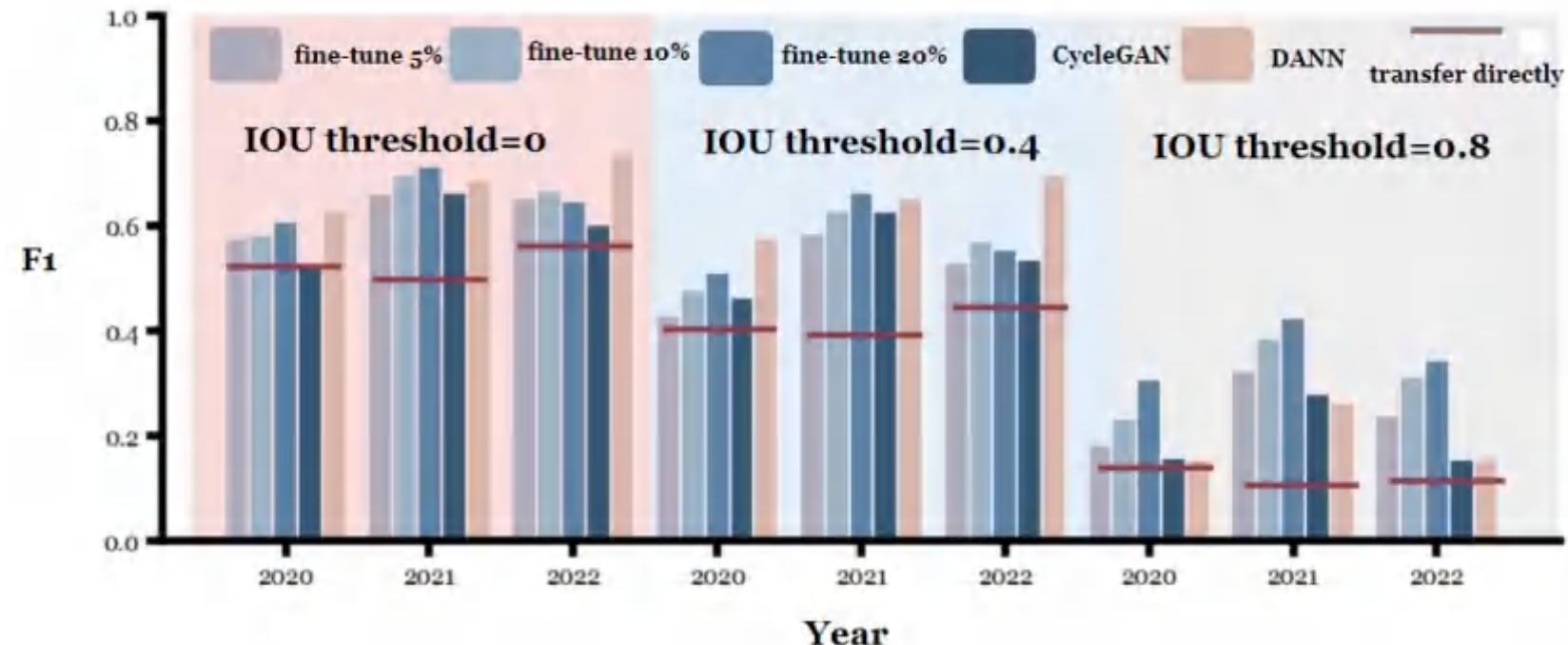
# 青藏高原北麓河地区热融滑塌多年期编目



## 域对抗神经网络 (Domain Adversarial NN)

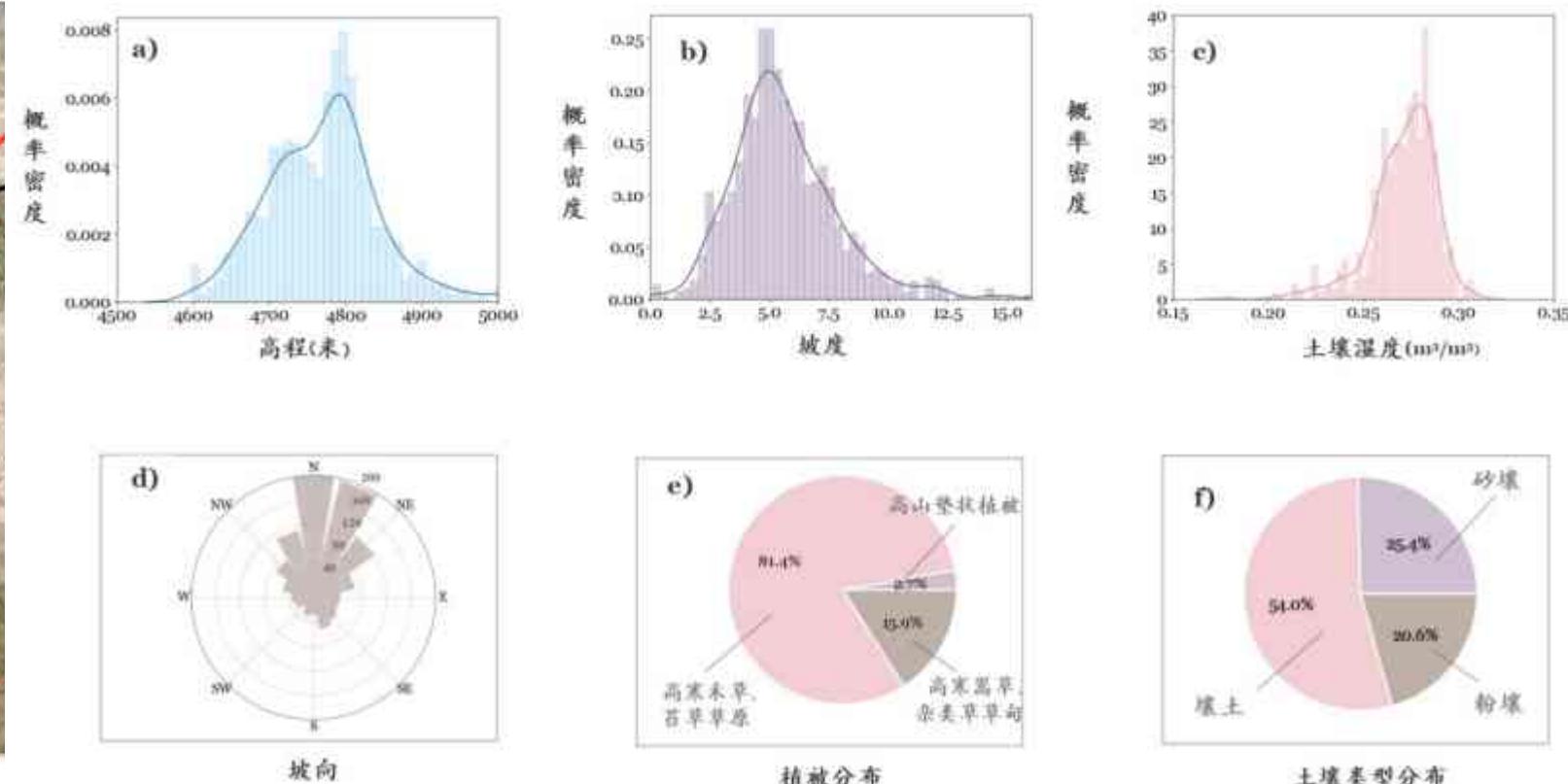
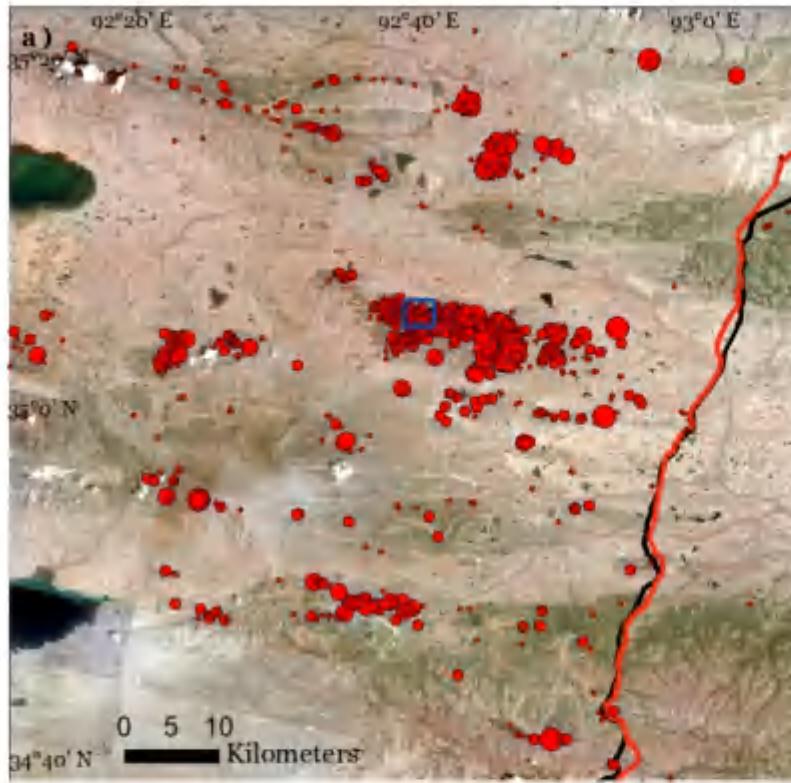
- 损失函数 Tversky loss
- 域对抗神经网络在损失函数中引入了梯度反转层 (Gradient reversal layer, GRL) 以实现特征提取器的梯度上升和域分类器的梯度下降
- 对于目标影像数据为多域或与源域差异较大的数据集，采用域对抗神经网络能够在中低阈值有效提升其迁移性能

# 青藏高原北麓河地区热融滑塌多年期编目



	F1相对于直接迁移的增量 e.g., IOU threshold = 0.4	能否解决与源域 差异较大	能否解决多域	人工成本
Fine-tune	0.026~0.269	√	√	需要目标类标签
CycleGAN	0.157~0.232	✗	✗	不必
DANN	0.173~0.259	√	√	不必

# 青藏高原北麓河地区热融滑塌多年期编目

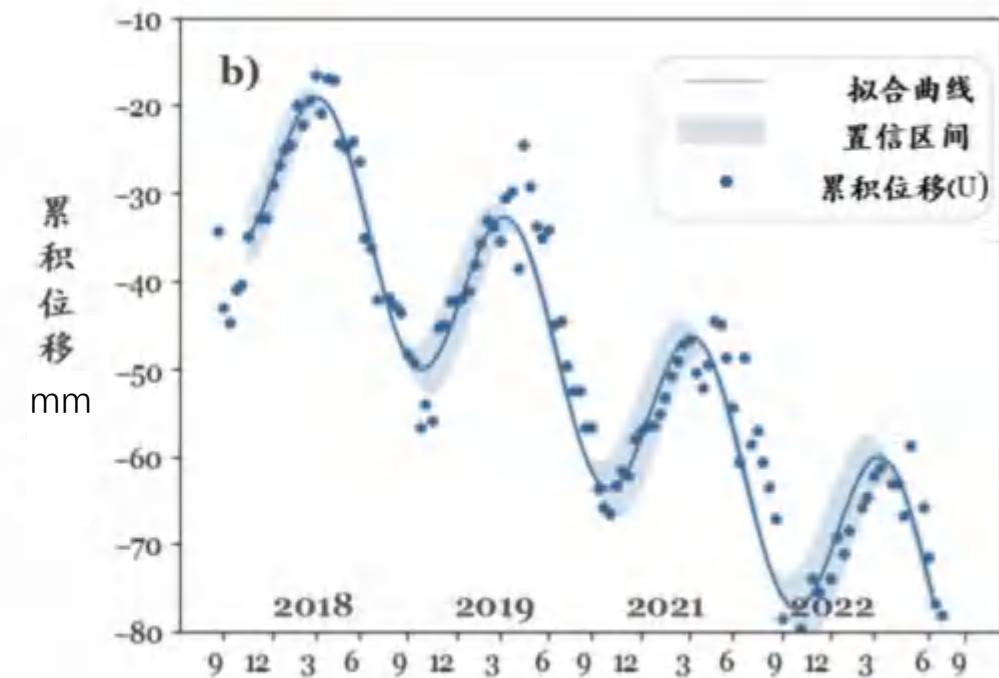


热融滑塌大多发育在土壤湿度较高、土质结构紧密、中等海拔的平缓阴坡

# 青藏高原北麓河地区热融滑塌多年期编目

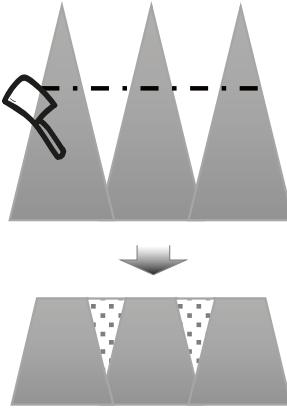
2019~2022年研究区内的热融滑塌

- 数目 803 ↗ 885
- 面积 1,727 ↗ 2,329 公顷
- 平均垂直形变速率为-13.28 mm/a





山体滑坡  
粘塑性滑坡  
水电站边坡  
热融滑塌陷



地面沉降  
地下水开采  
削山造城  
煤矿开采

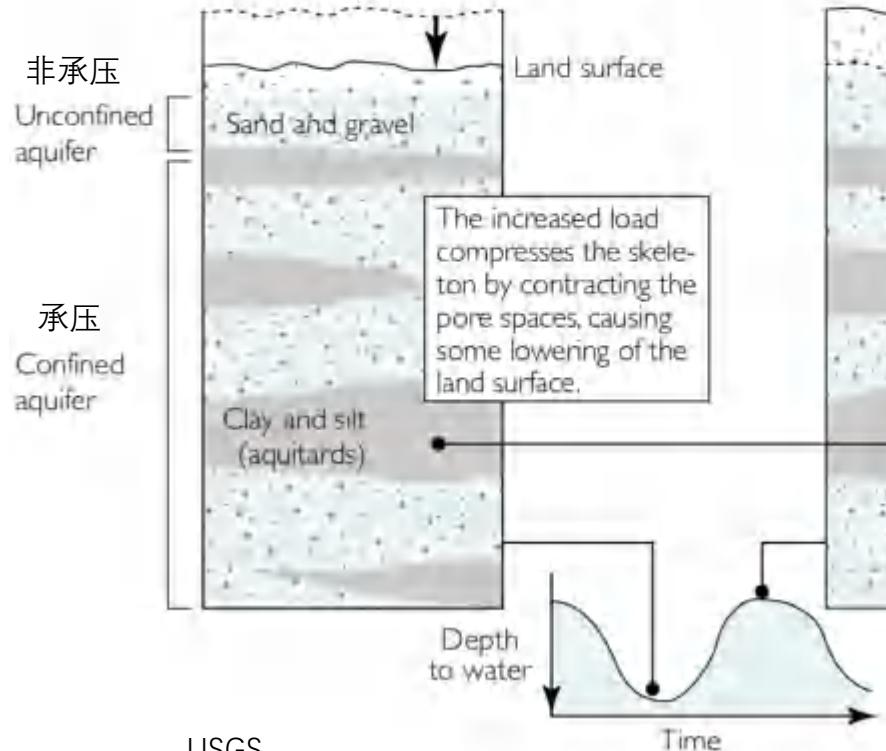


地震震损

# 地下水开采

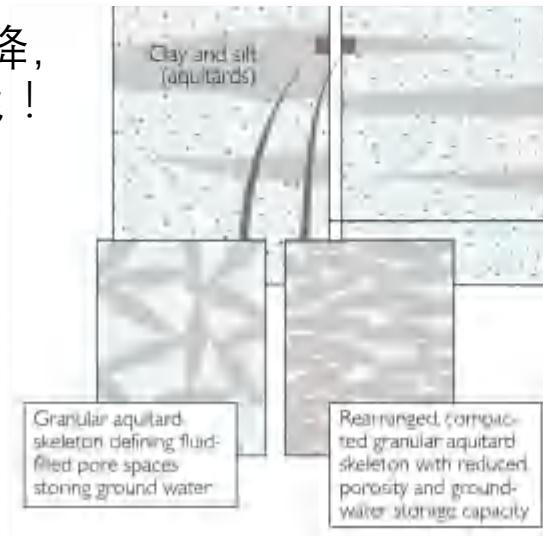
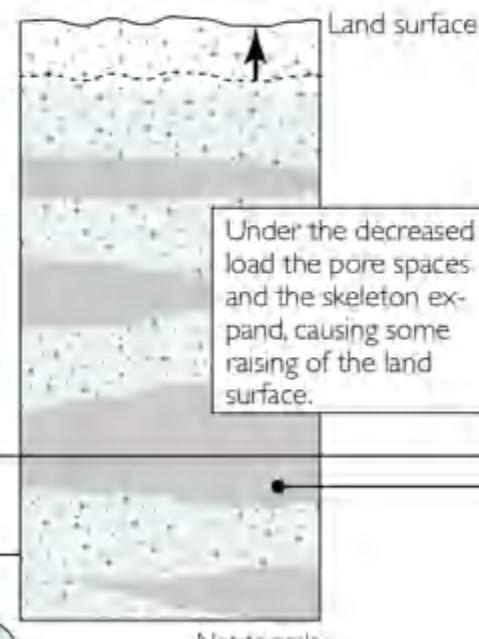
一旦发生不可逆转的非弹性沉降，  
地下含水层将失去其储水功能！

When water levels drop, due mainly to seasonal increases in ground-water pumping, some support for the overlying material shifts from the pressurized fluid filling the pores to the granular skeleton of the aquifer system.

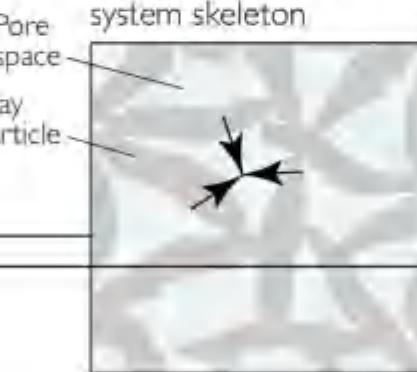


USGS

When ground water is recharged and water levels rise, some support for the overlying material shifts from the granular skeleton to the pressurized pore fluid.

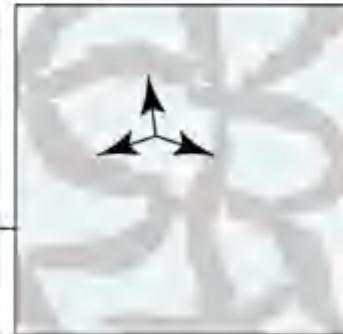


Contracting aquifer-system skeleton



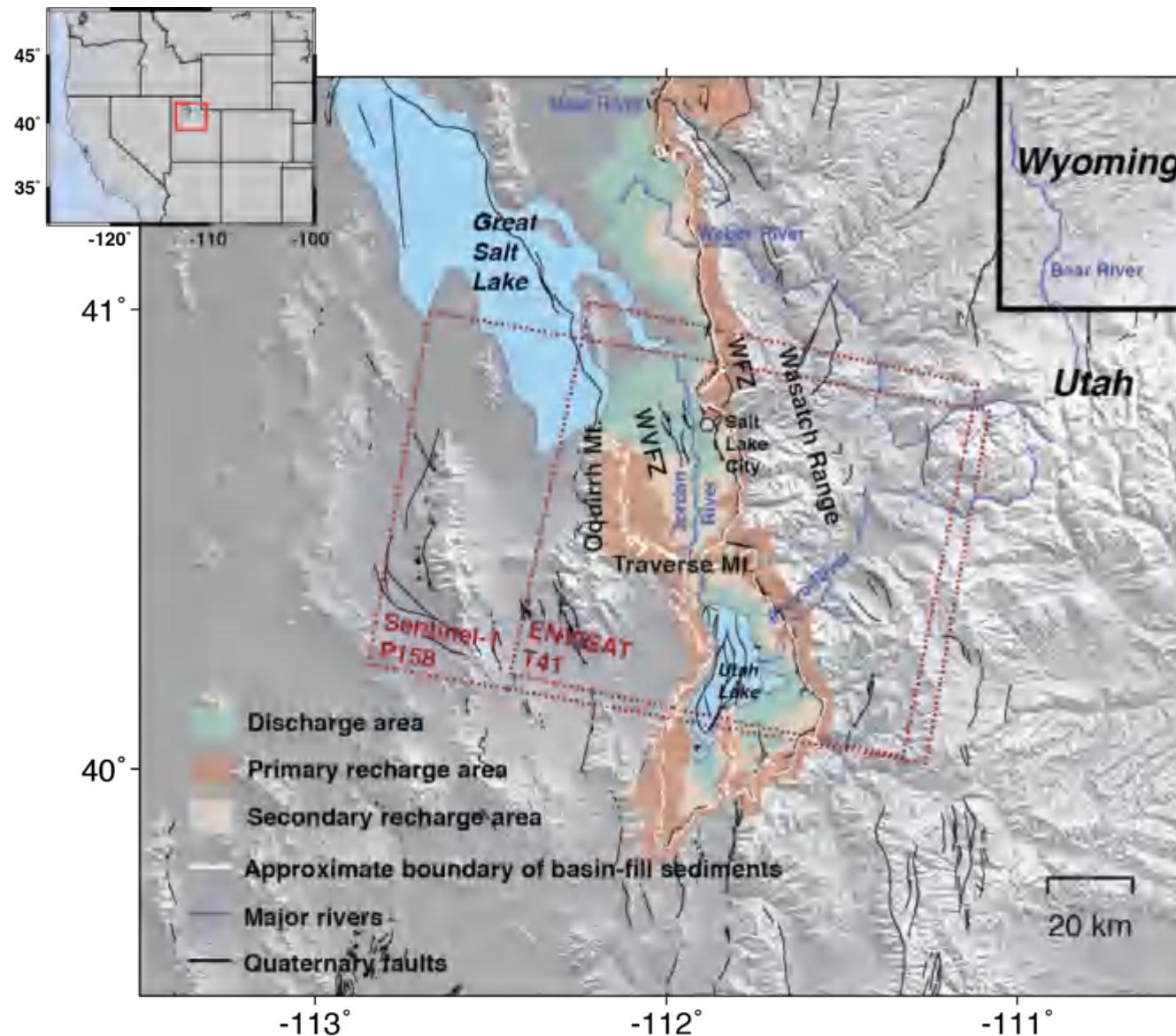
Decreased fluid pressure causes the skeleton to contract, creating some small subsidence of land surface.

Expanding aquifer-system skeleton

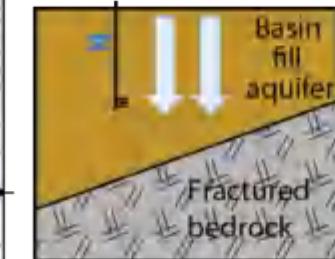


Increased fluid pressure expands the skeleton, creating some small uplift of land surface.

# 美国犹他州盐湖城地下含水层

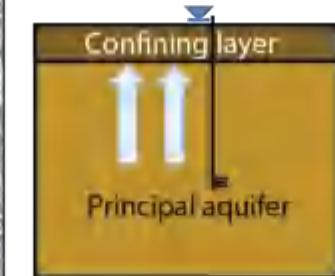


Primary recharge area

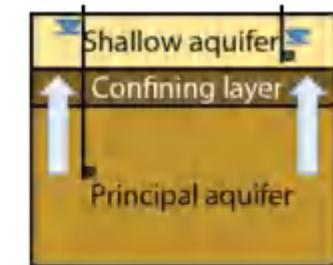


补水区

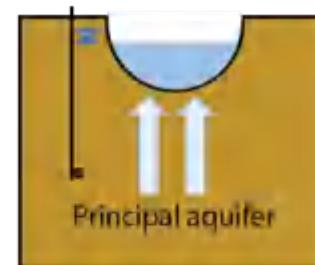
Discharge area - confined aquifer



排水区



Discharge area - unconfined aquifer

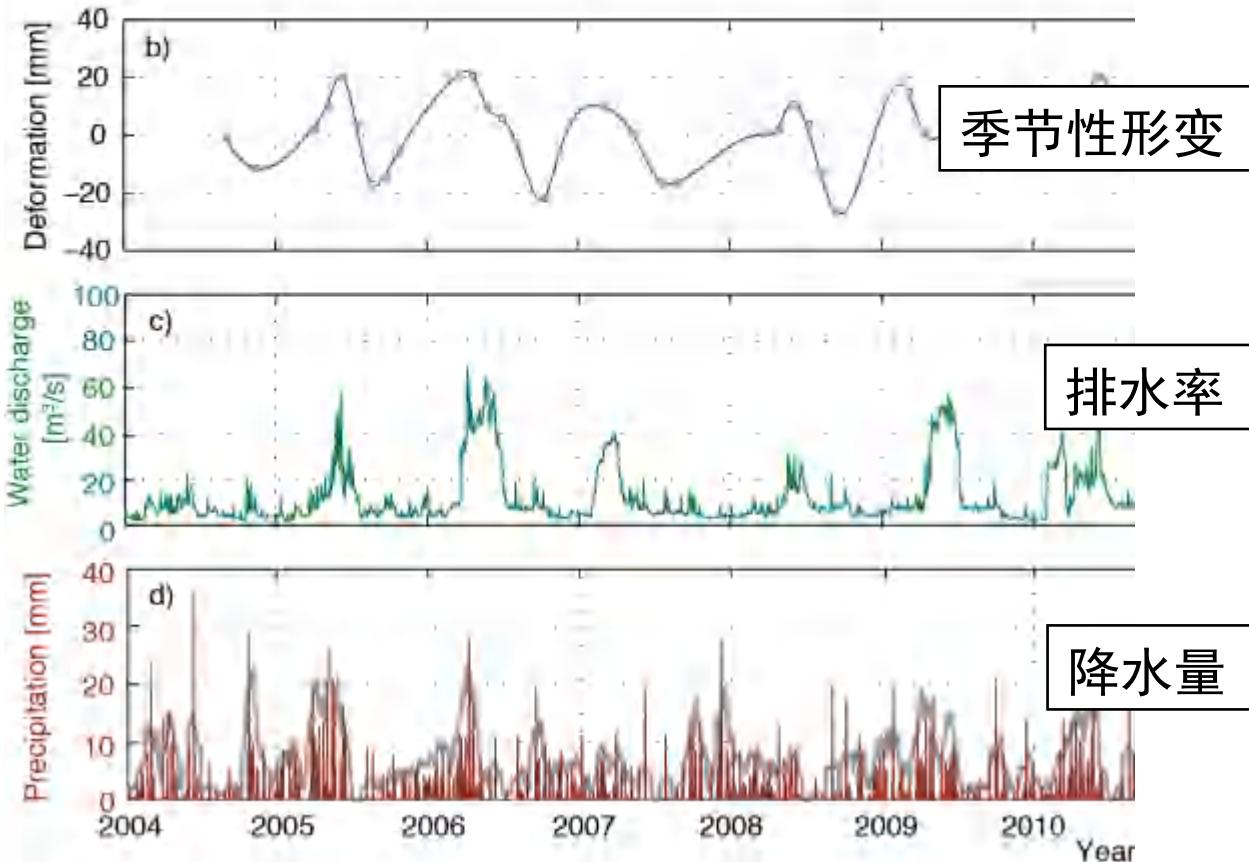


Not to scale

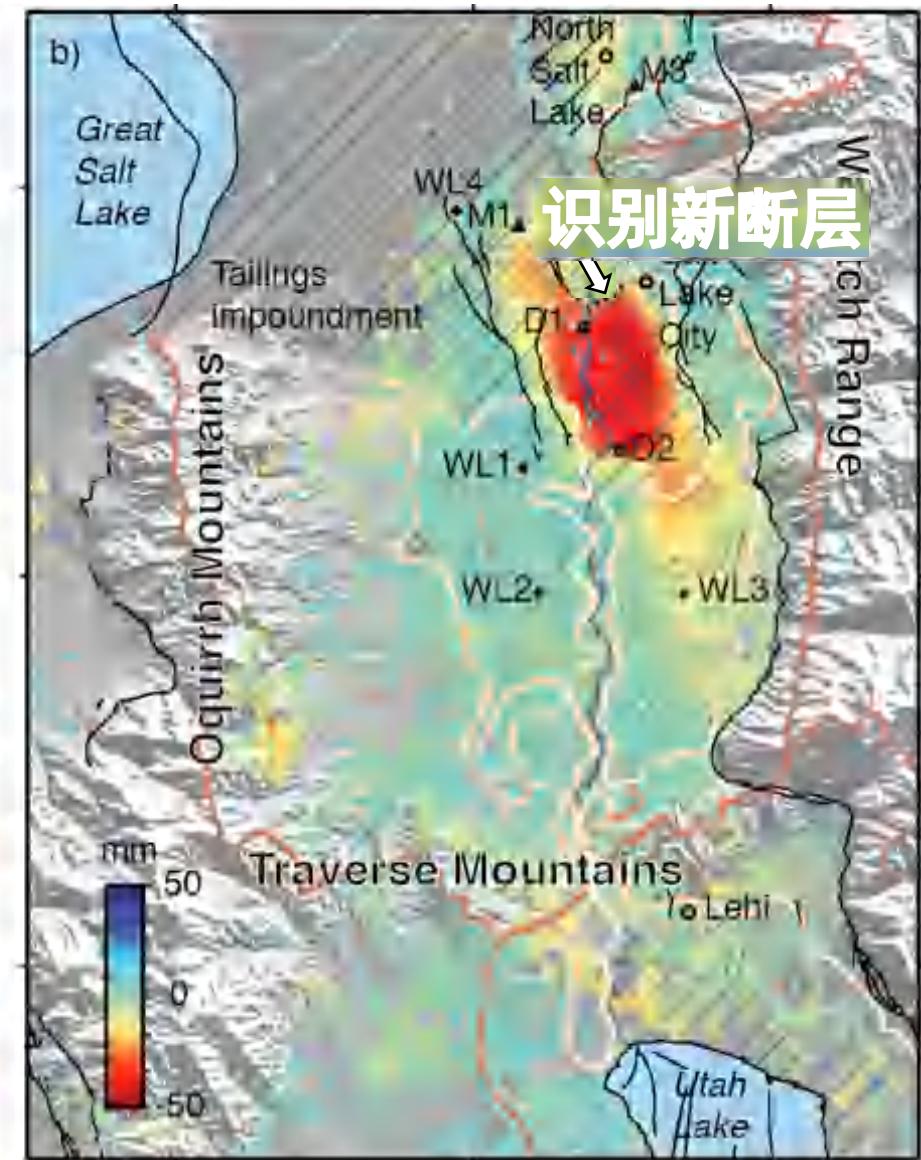
# 美国犹他州盐湖城地下含水层

- 季节性地表形变与地下水位相关性

季节性地表呼吸  $\leftrightarrow$  季节性水位变化

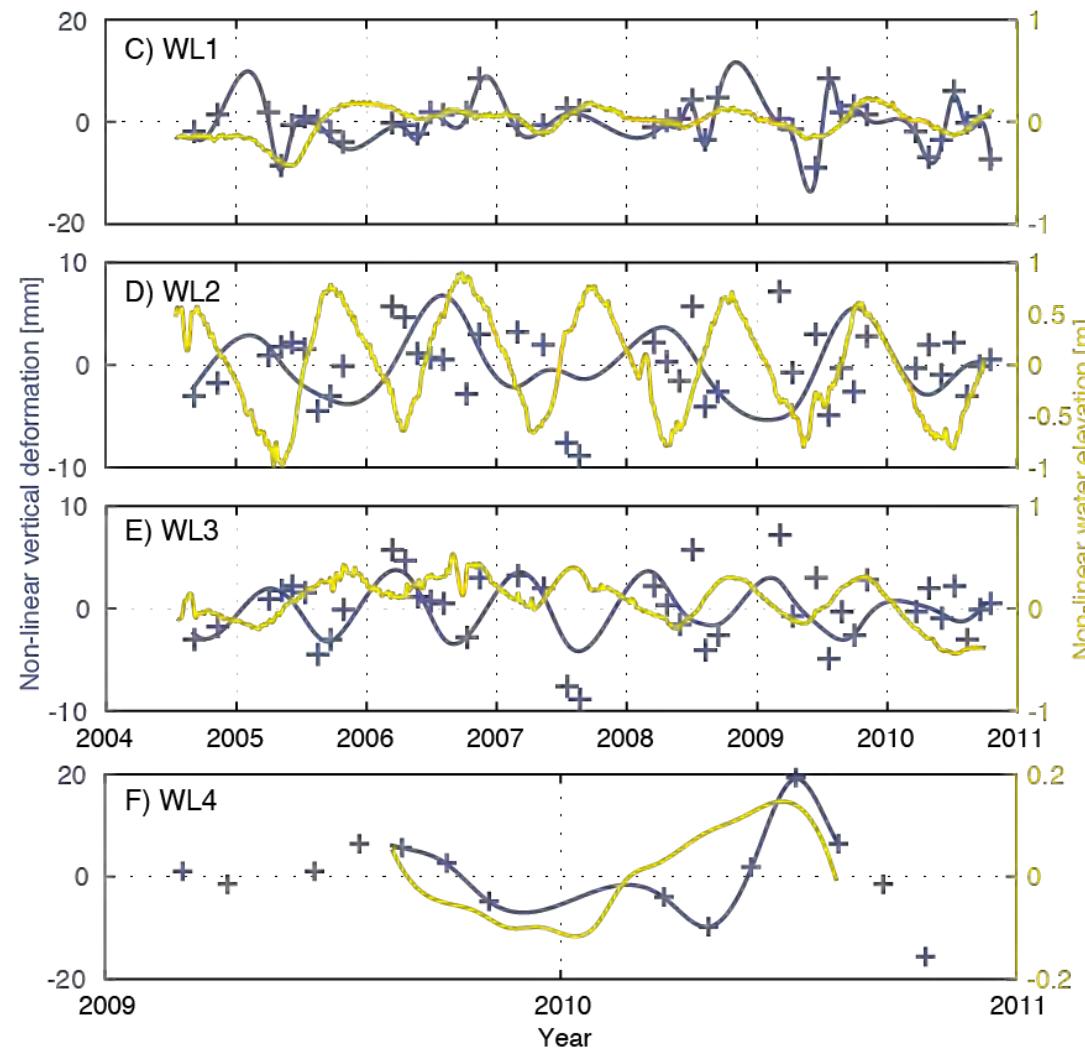


季节性形变幅度



# 美国犹他州盐湖城地下含水层

- 为定量、规律地提取地下水储量提供新方案

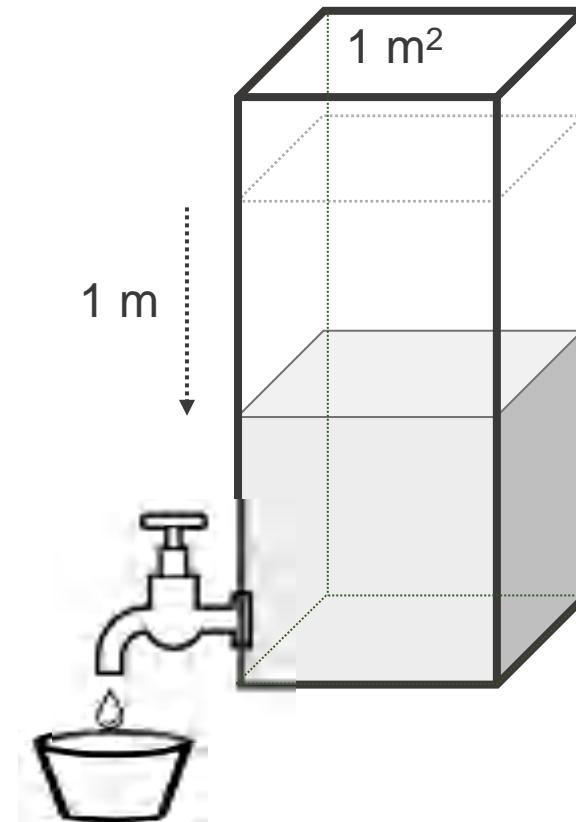


弹性蓄水系数

$$S = \frac{d(t)}{h(t)}$$

垂直形变 (去趋势)  
地下水位 (去趋势)

$$\|d_{detrend}(t + \tau) - S \times h_{detrend}(t)\|$$



# 美国犹他州盐湖城地下含水层

- 解算区域性水文地质参数

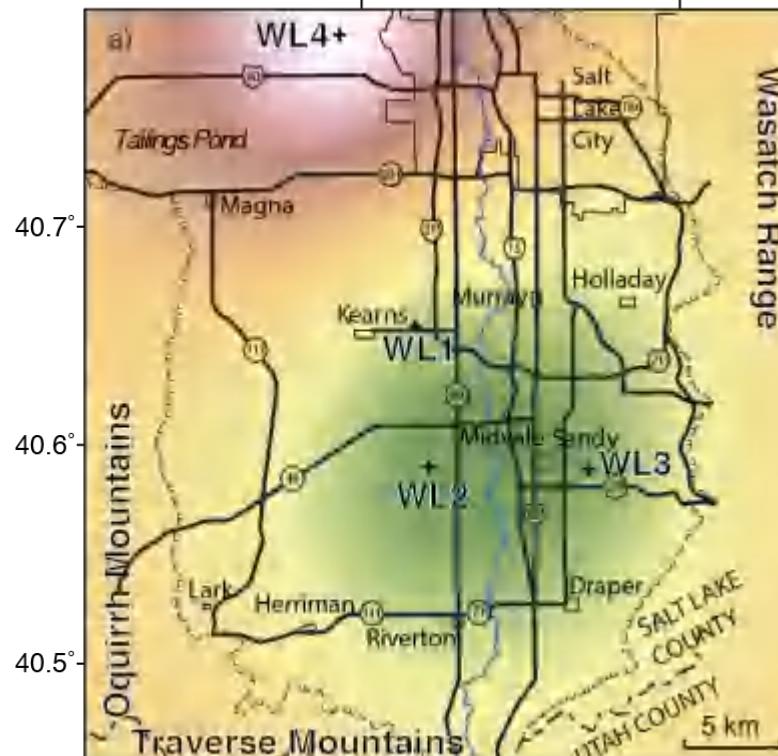
弹性蓄水系数  
特定弹性蓄水系数

$$S = d(t)/h(t)$$

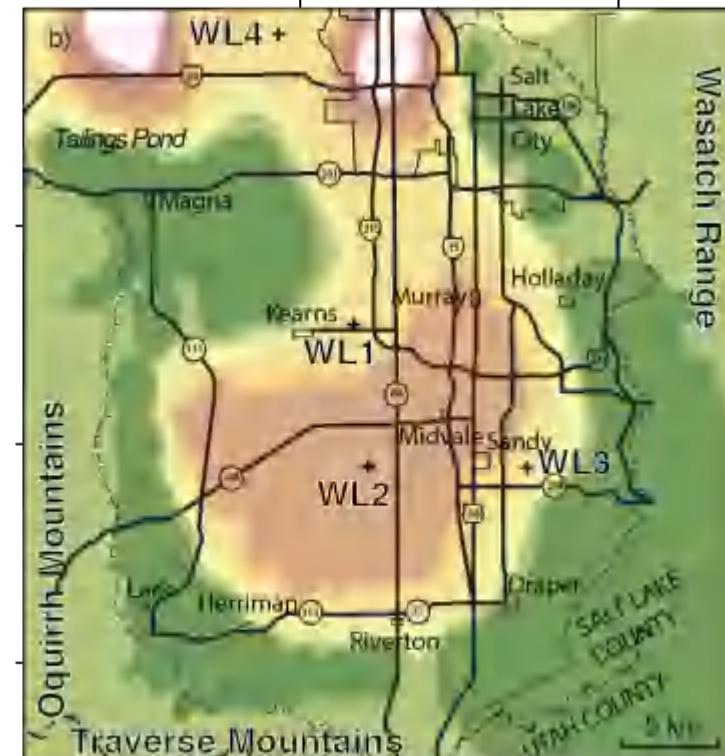
$$S_s = S/b$$

$$S_s = \rho g(\alpha + n\beta)$$

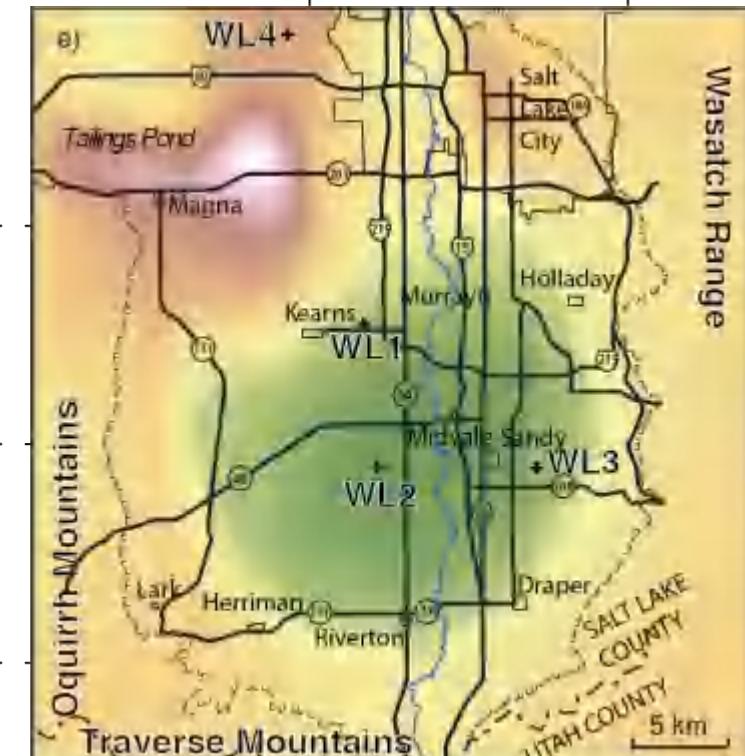
蓄水系数



含水层厚度 ( $b$ )



含水层压缩性 ( $\alpha$ )



0.0020 0.0668

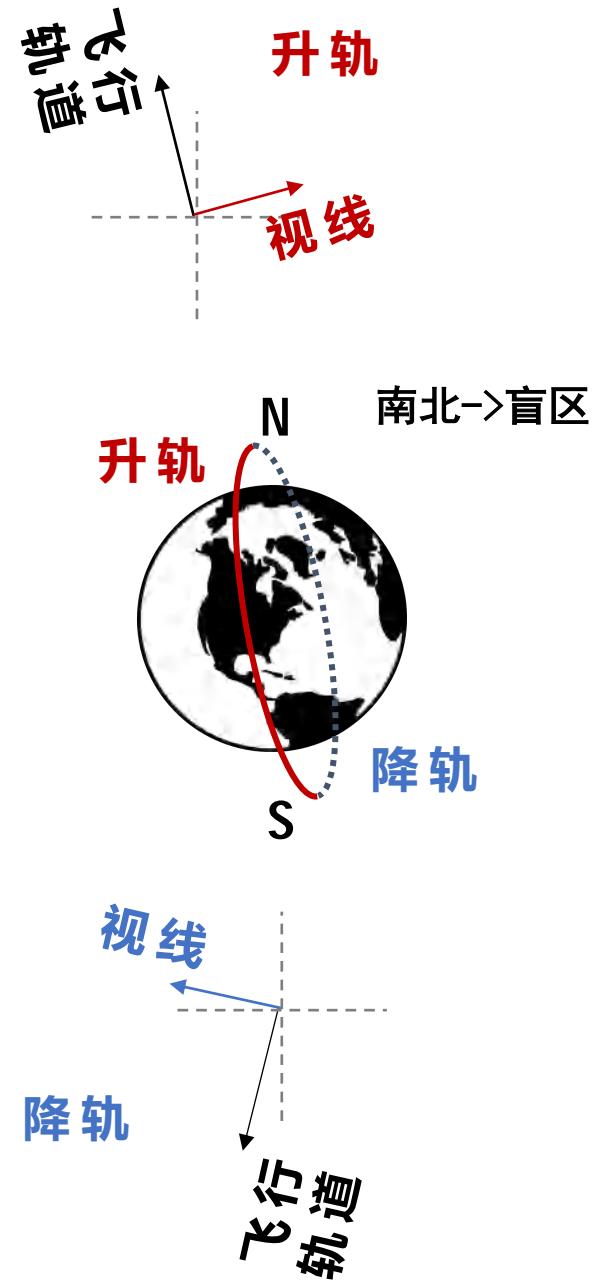
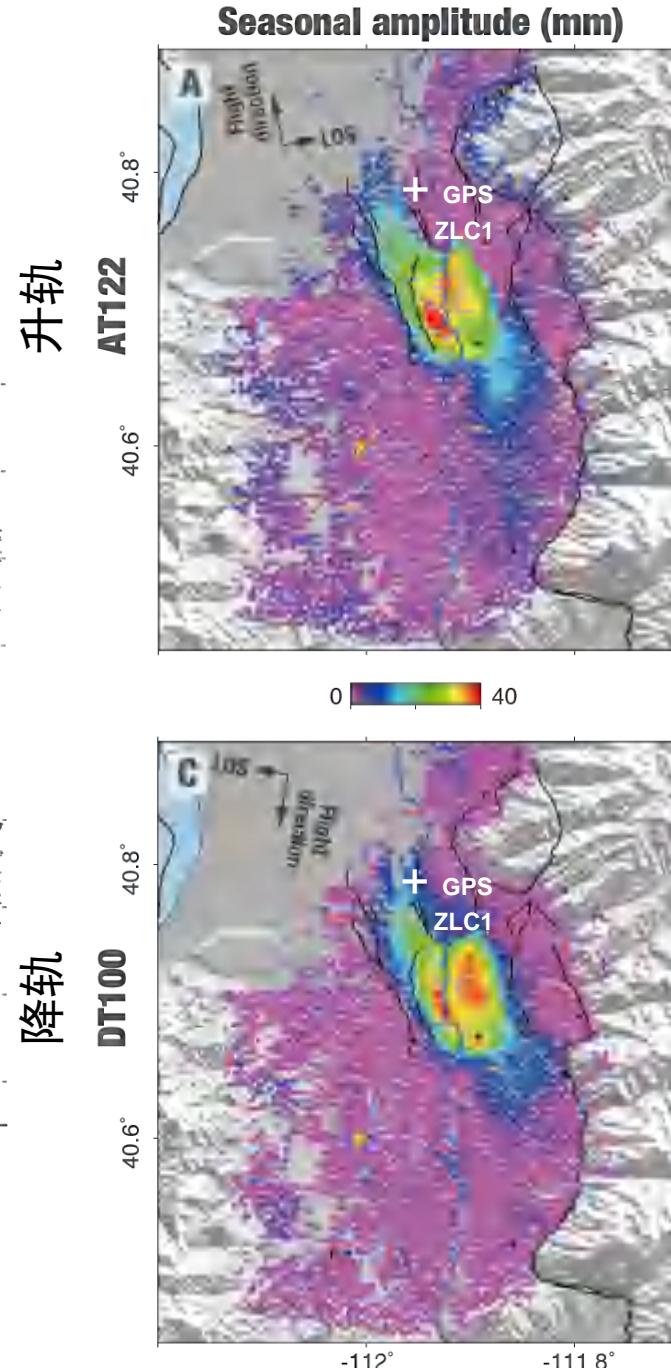
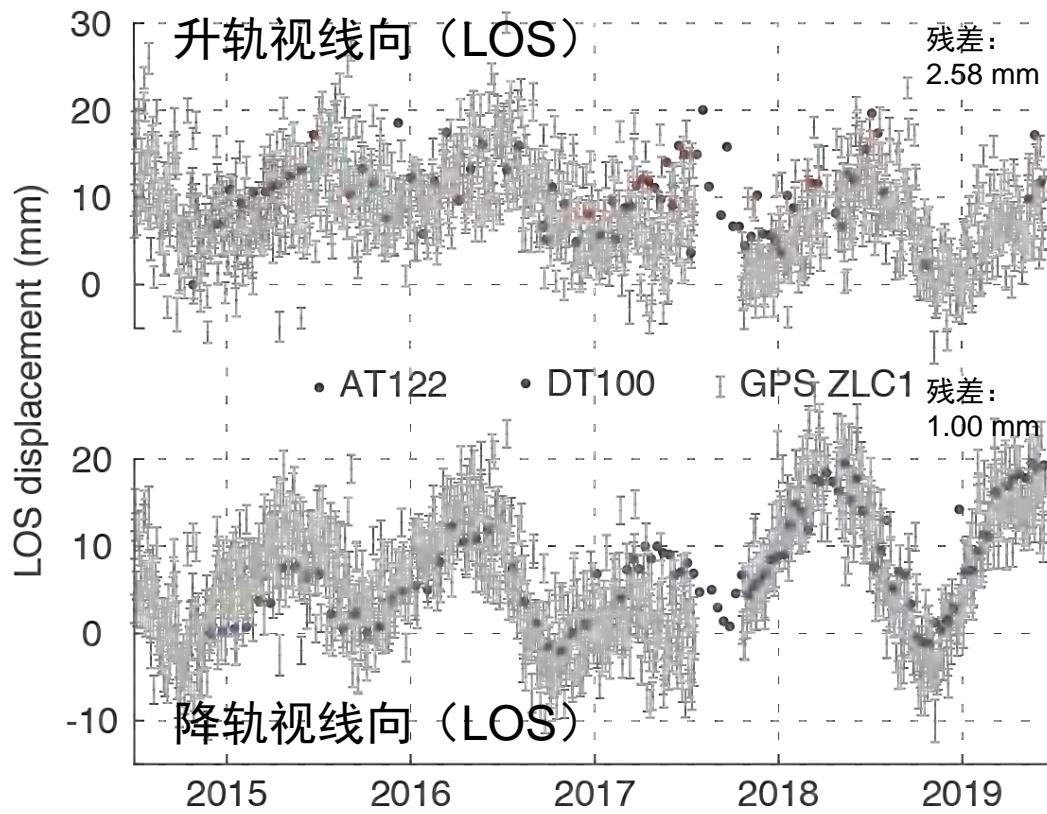
305 m 1220

2.05e-10 m<sup>2</sup>/N 1.43e-8

# 美国犹他州盐湖城地下含水层

- Sentinel-1 升降轨时空形变

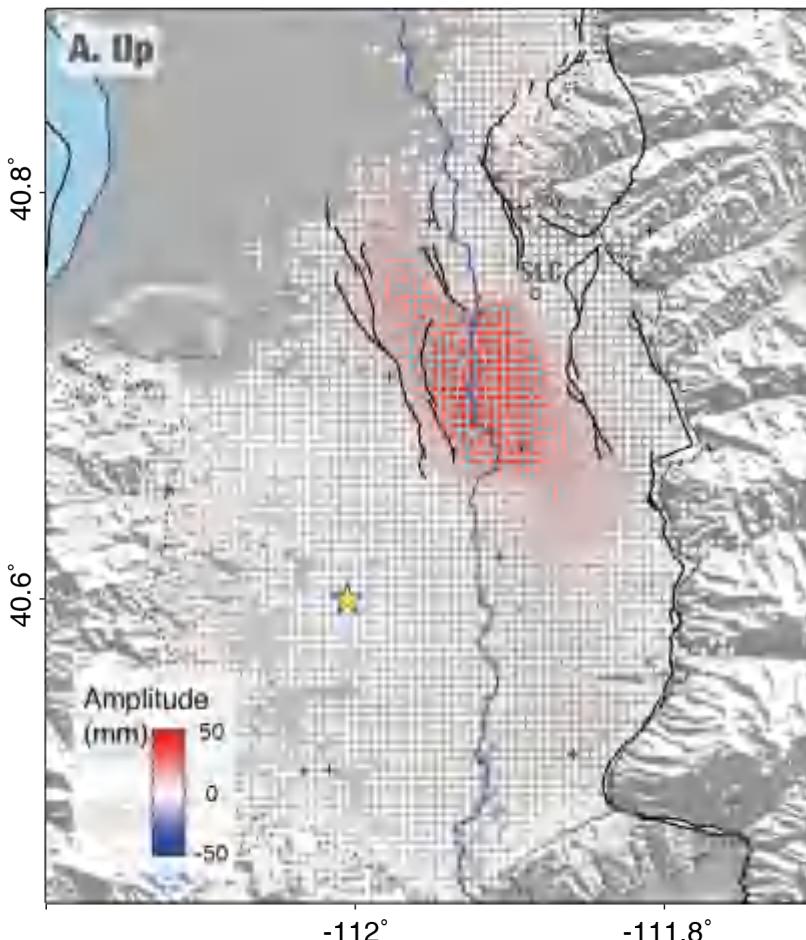
A. LOS vs GPS



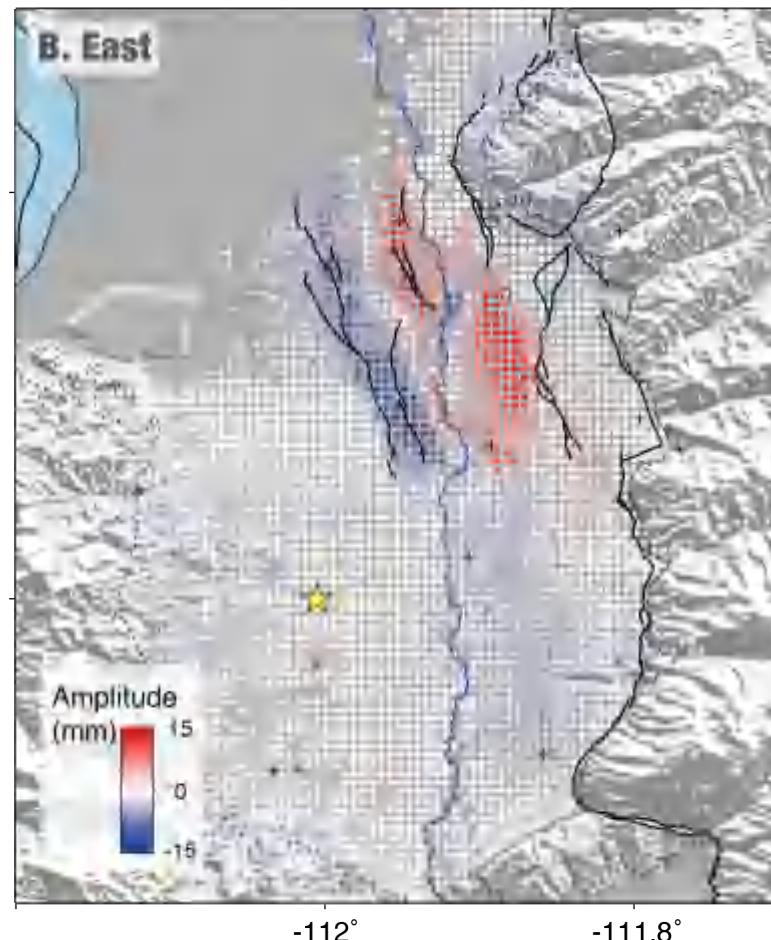
# 美国犹他州盐湖城地下含水层

- 二维季节性形变幅度 (e.g., 冬季)

垂直方向

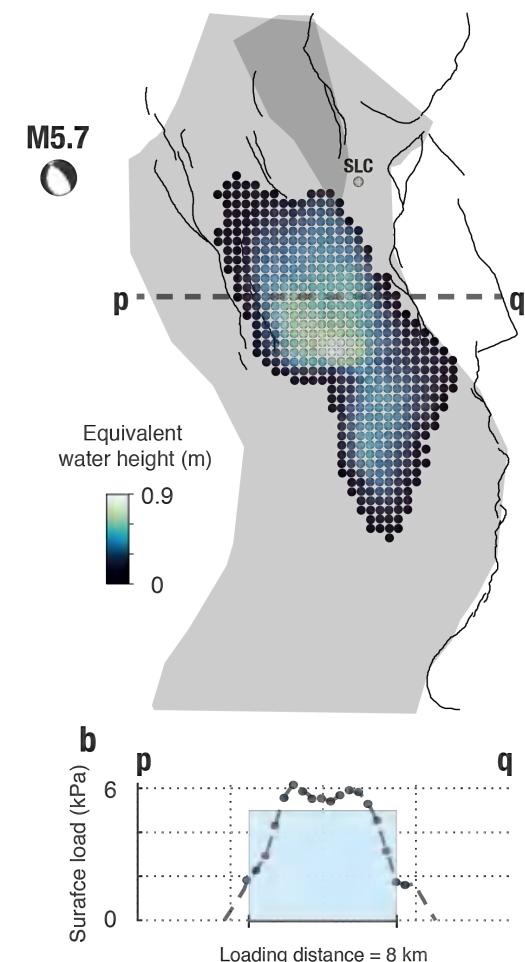


东西方向



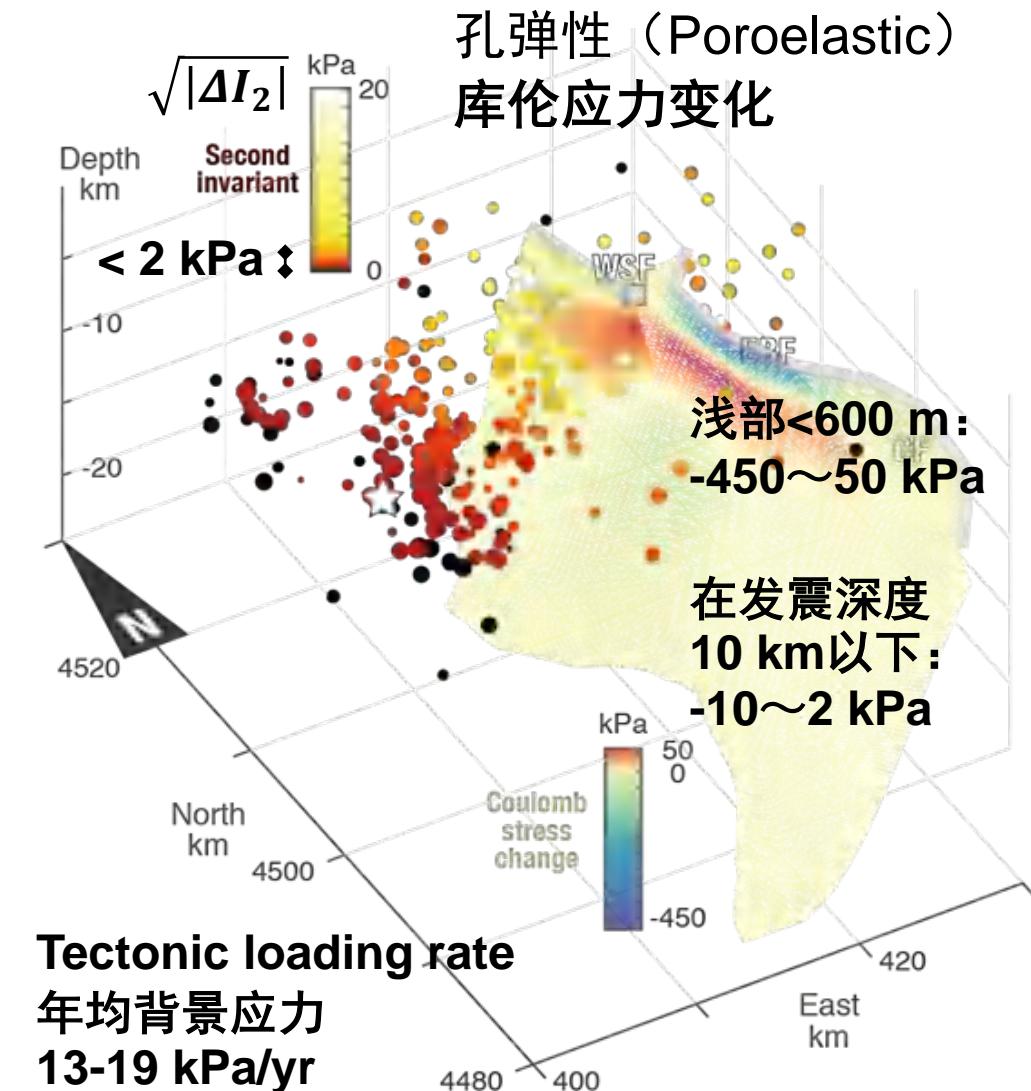
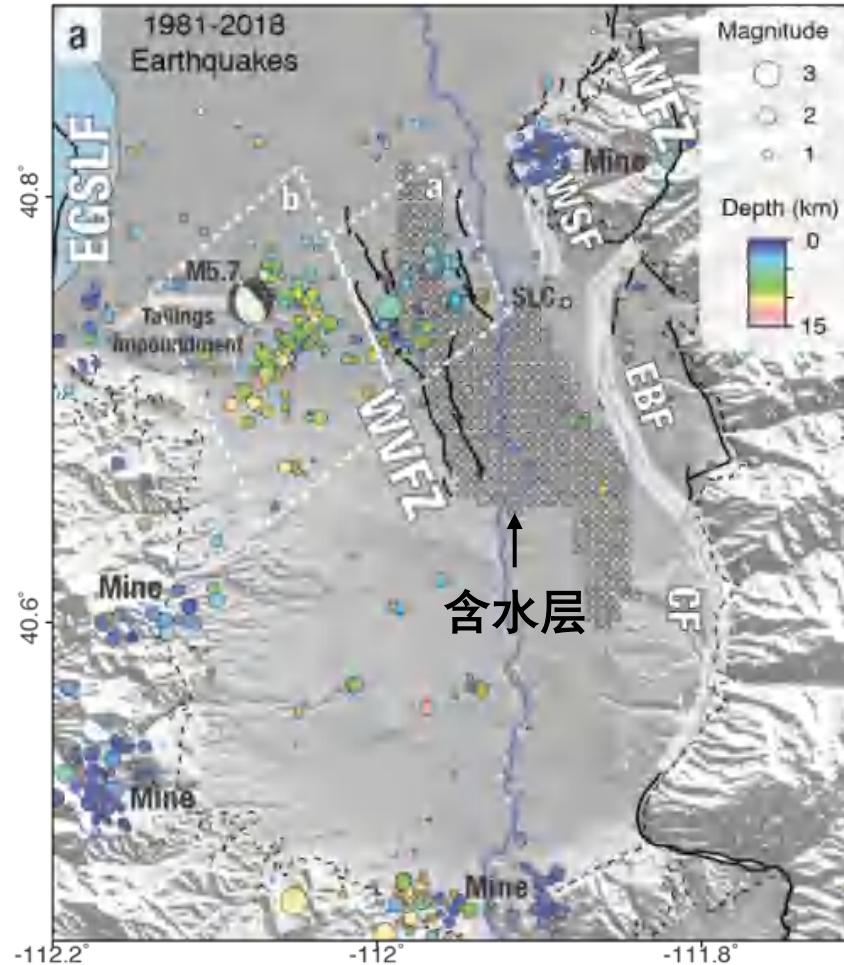
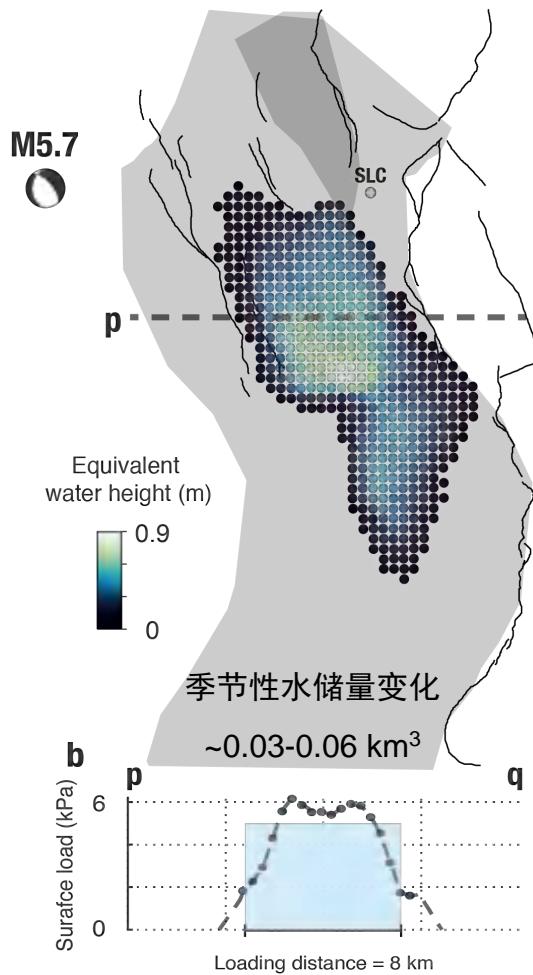
季节性水储量变化

~0.03-0.06 km<sup>3</sup>



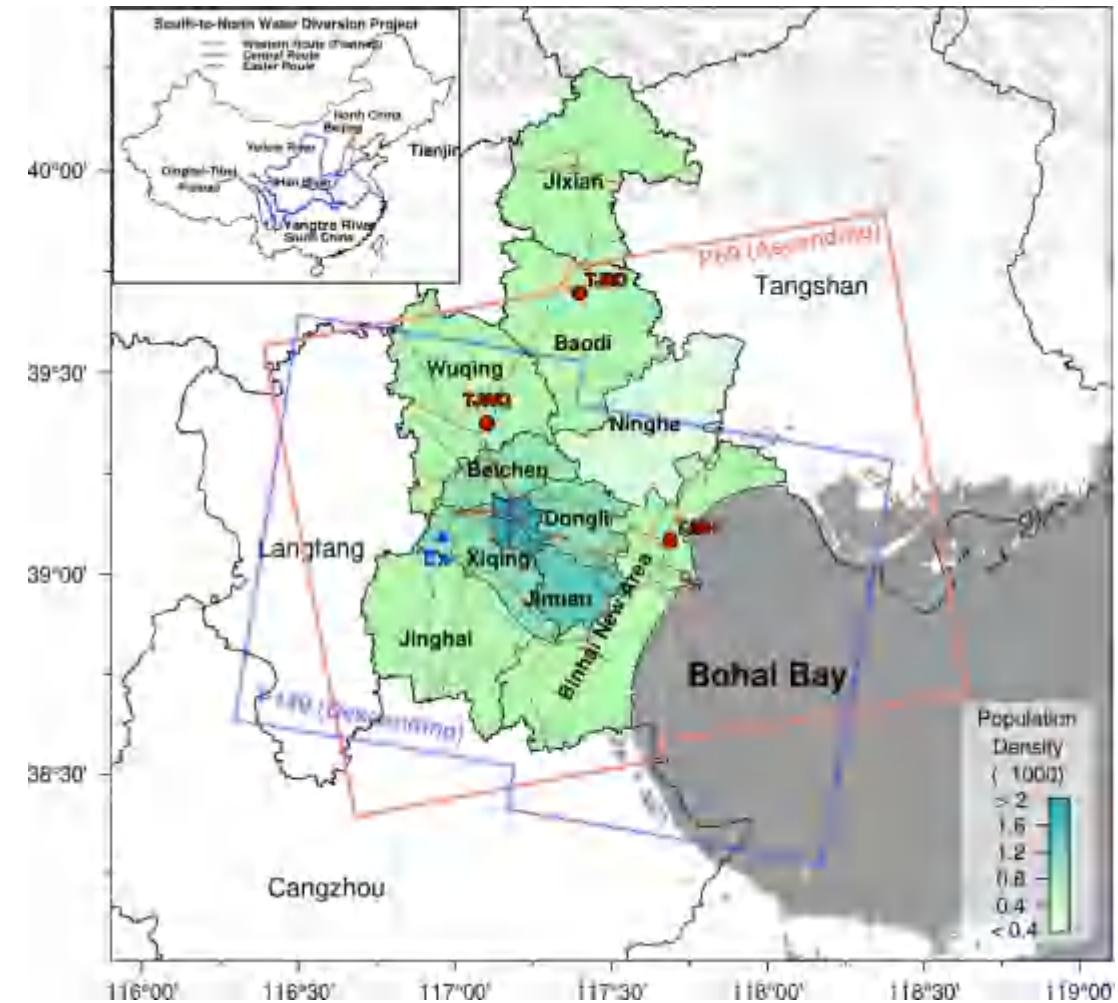
# 美国犹他州盐湖城地下含水层

- 含水层季节性孔弹性 (Poroelastic) 应力扰动



# 京津冀地面沉降

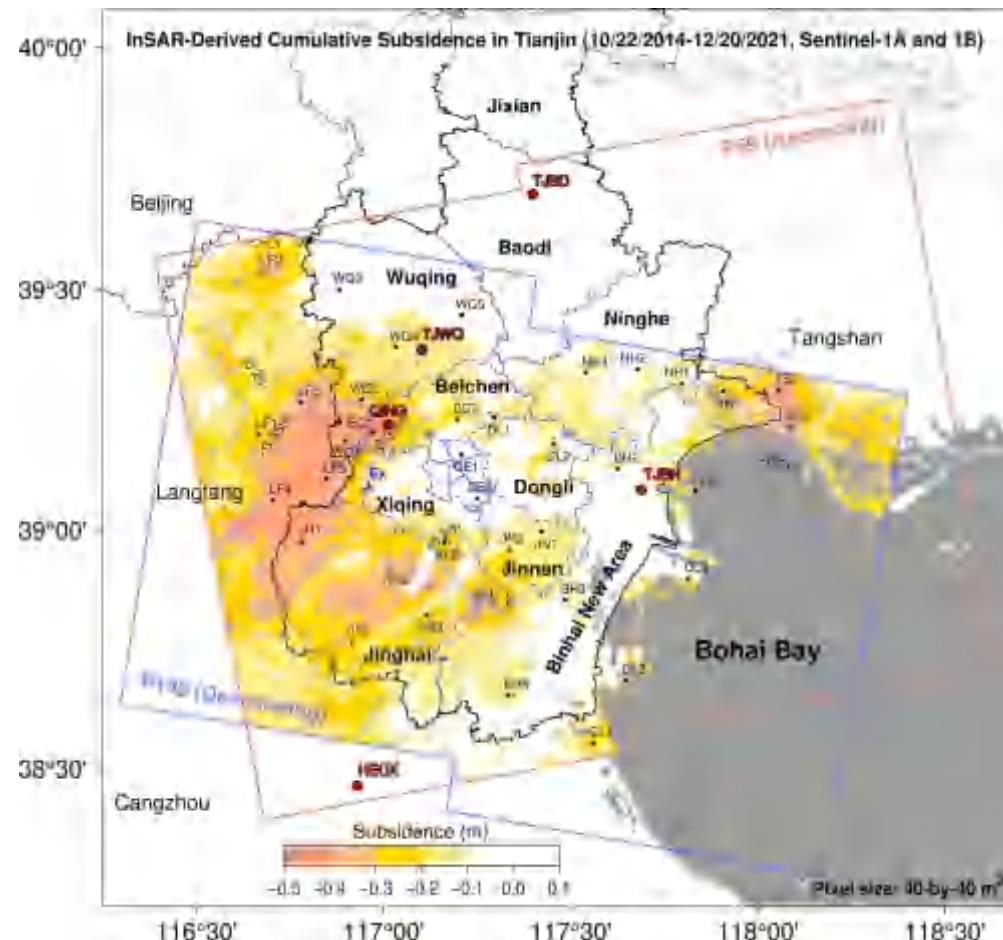
- 我国重要港口城市 ( $11,760 \text{ km}^2$ , >13 million population)
- 地下水超采严重, 超采面积达  $9,440 \text{ km}^2$ , 深层地下水漏斗面积  $6,624 \text{ km}^2$ , 地面沉降问题突出



# 京津冀地面沉降

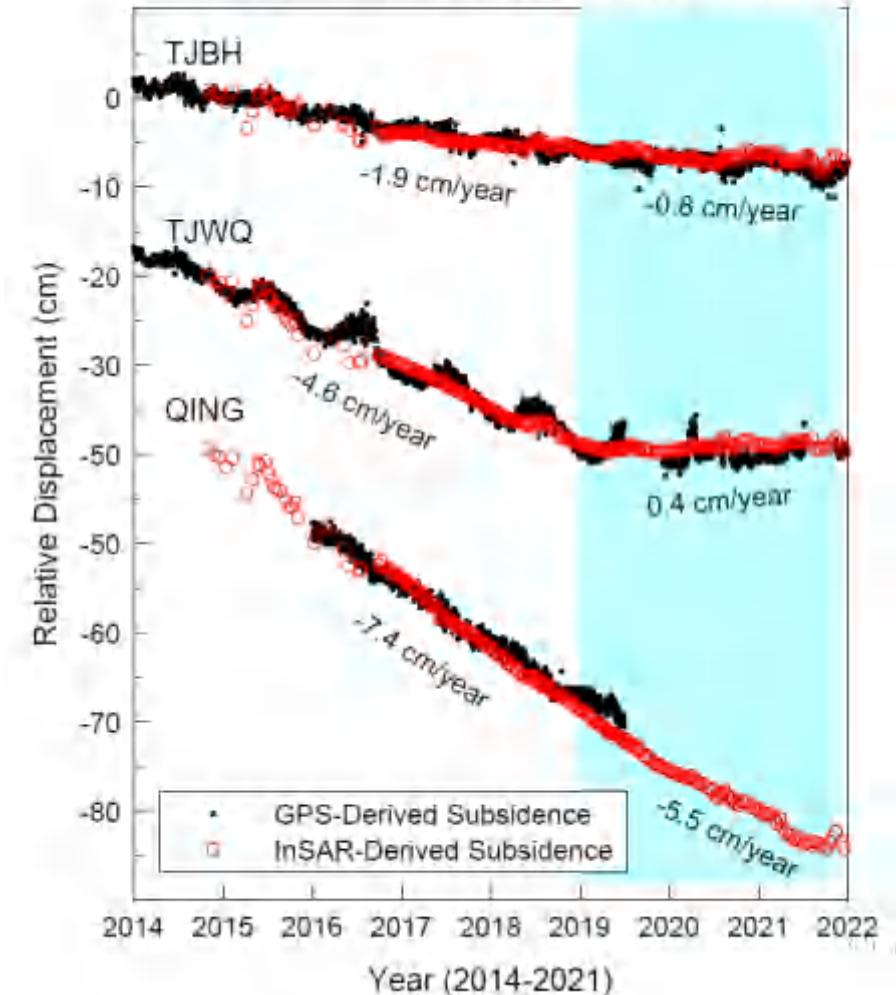
2014-2021地表形变:

- 有一万多平方公里的区域的累计形变超过10 cm
- 超过半米沉降区域包括武清区西南部和河北省东部



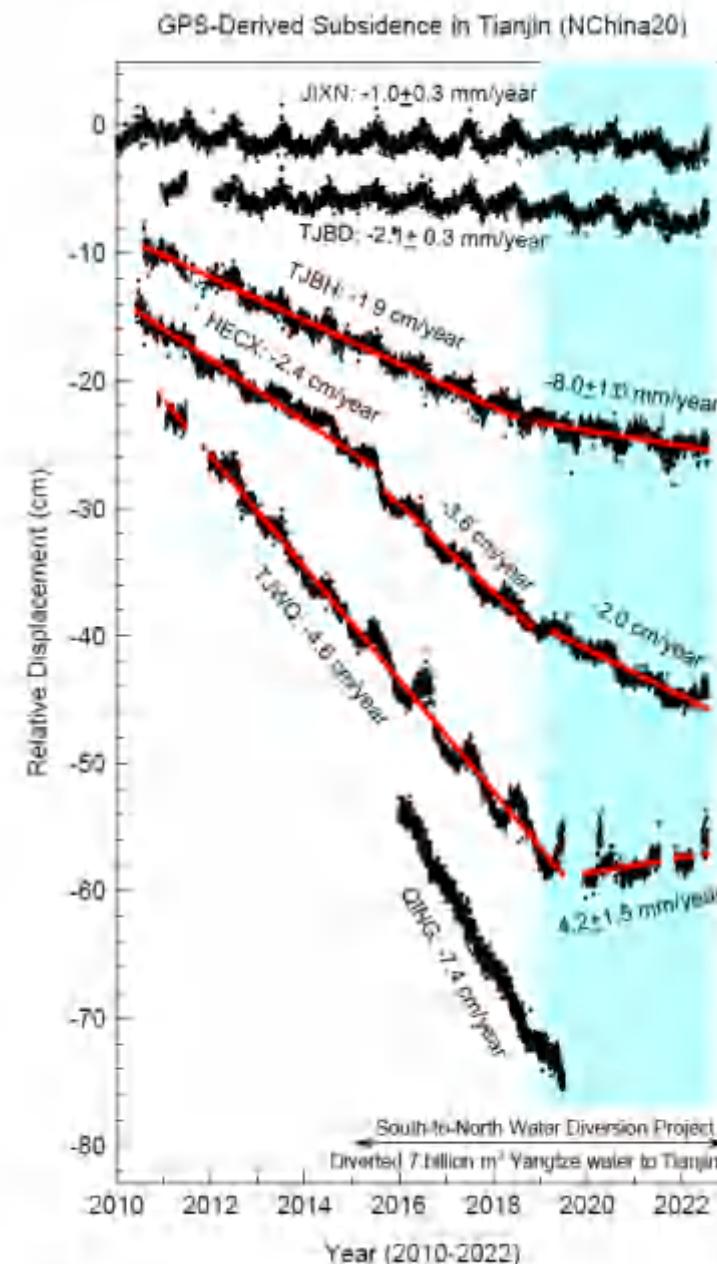
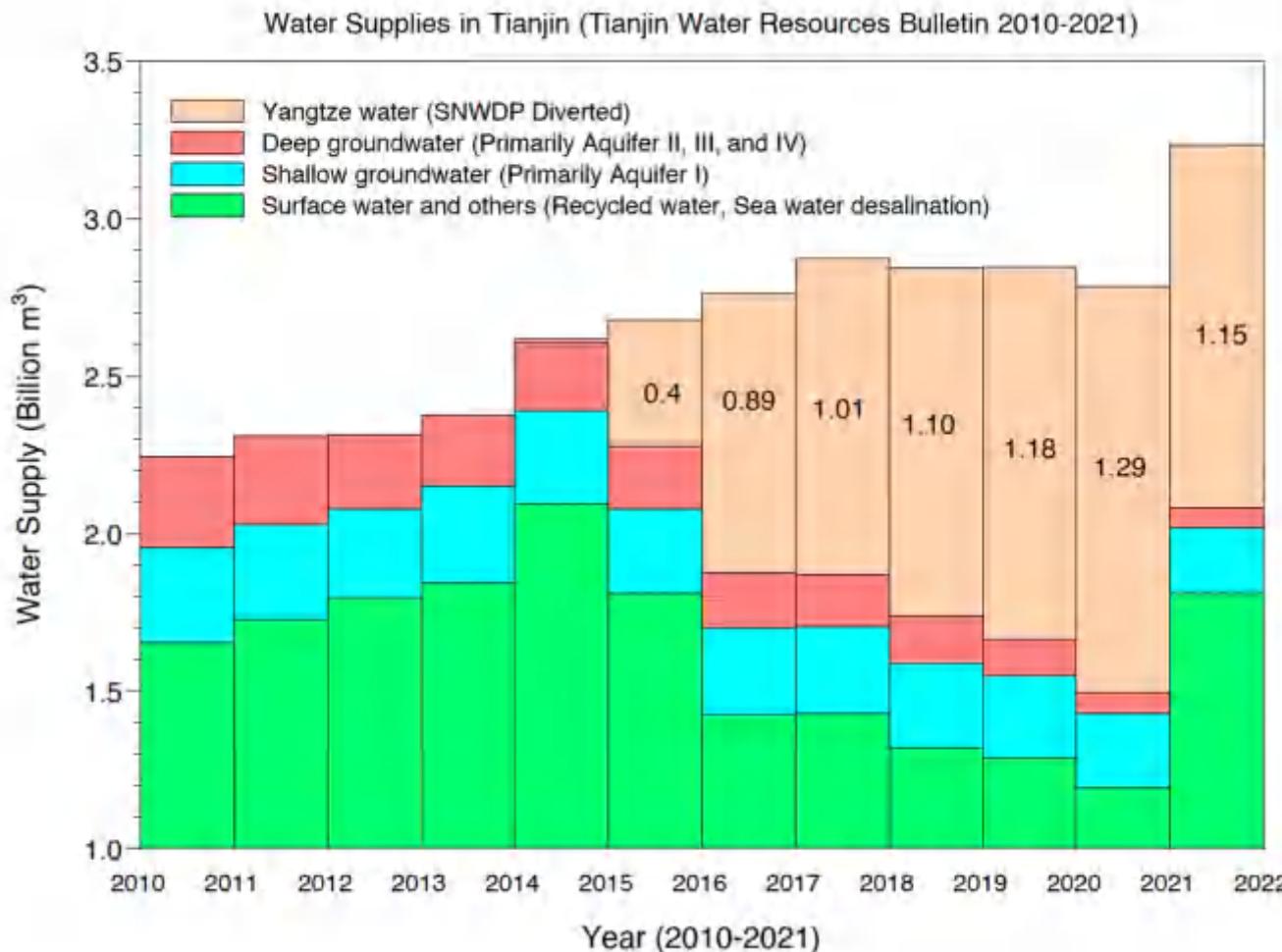
InSAR与GPS地面沉降监测结果交叉验证

Land Subsidence Time Series (NChina20)



# 京津冀地面沉降

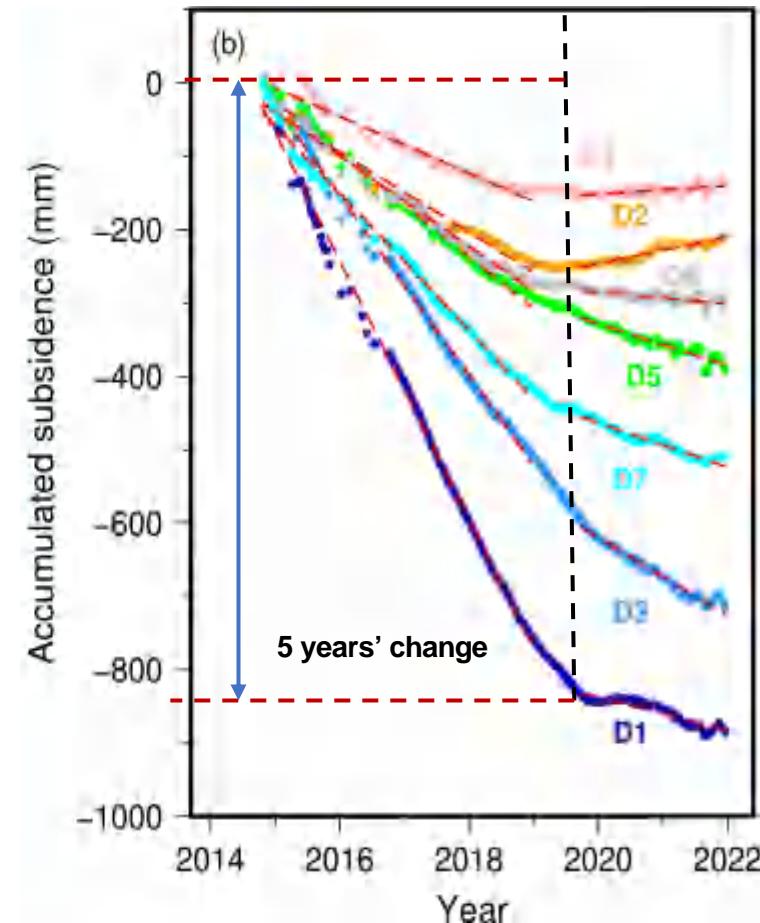
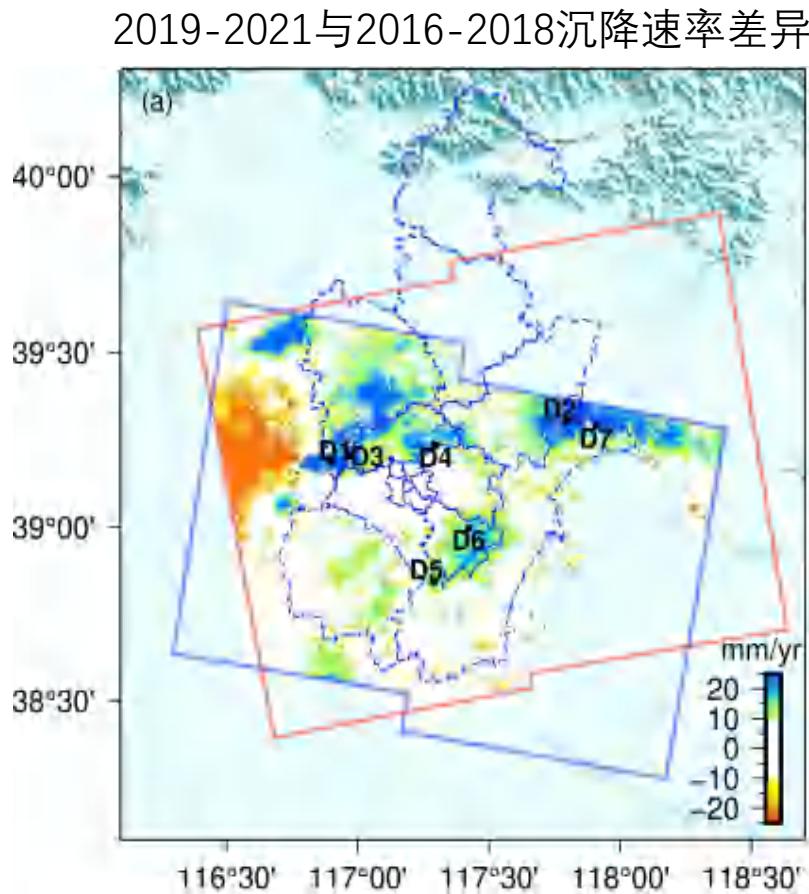
- 南水北调中线一期工程2014年12月正式通水
- 2019年1月《华北地区地下水超采综合治理行动方案》



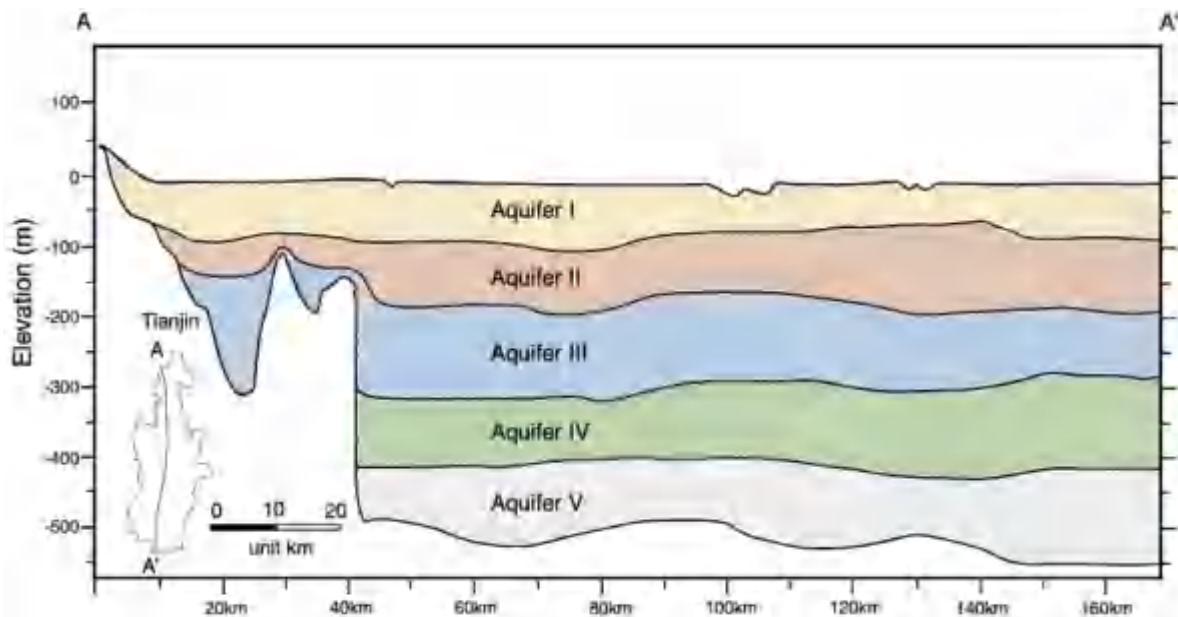
# 京津冀地面沉降

- 2019年起天津市地面沉降显著缓解，超50 mm/yr的快速沉降区从2016-2018的440 km<sup>2</sup>缩至2019-2021的280 km<sup>2</sup>，减幅达到36%，武清区北部、宁河区东部出现了回弹

**南水北调和治理超采的政策成效显著**



# 京津冀地面沉降



## Aquifers

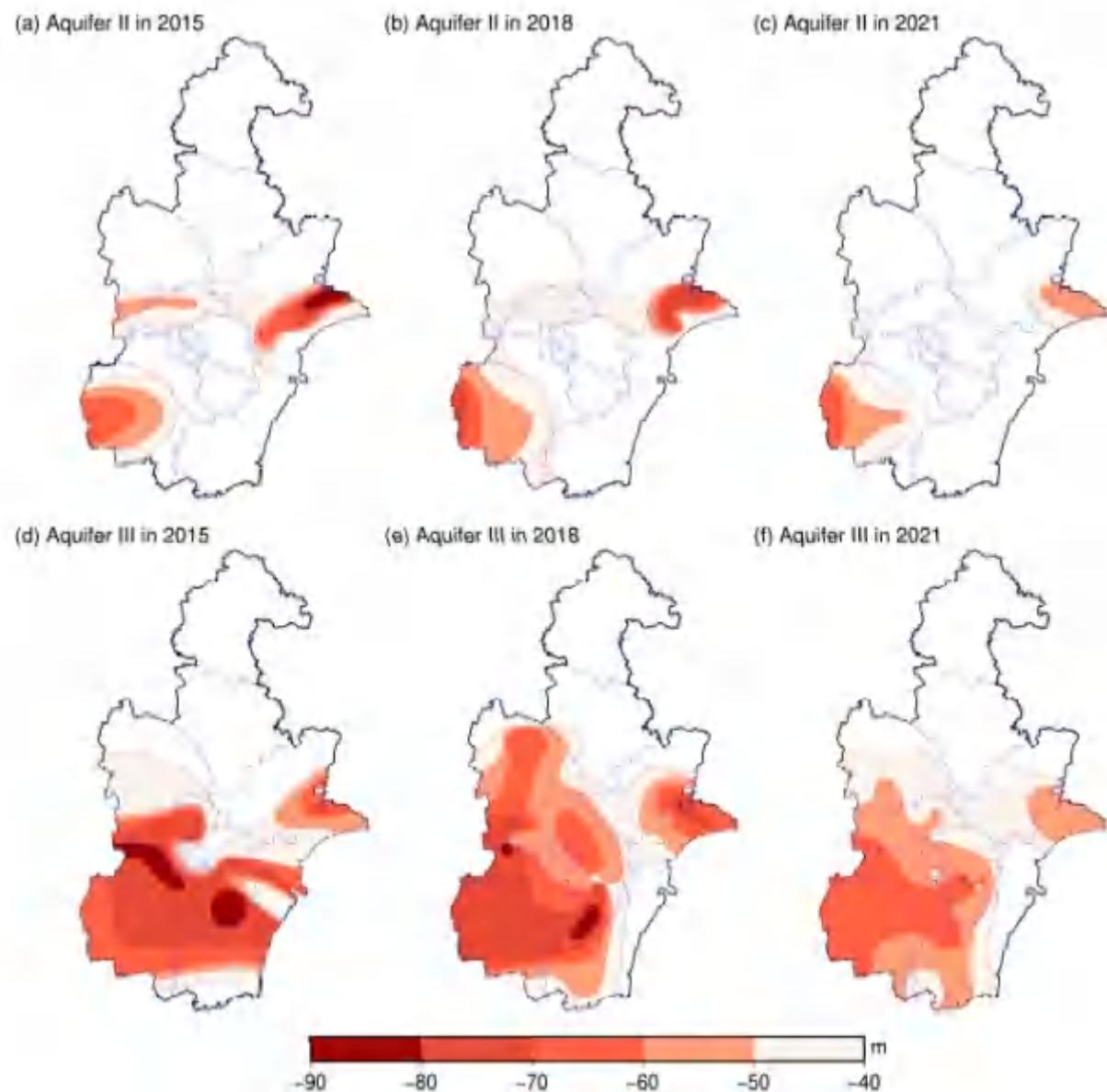
**Aquifer I:** Freshwater zone: medium-coarse sand with gravel and medium-fine sand  
Saline water zone: fine and silty sand

**Aquifer II:** Mainly sand with gravel, silty sand, fine sand and medium-fine sand

**Aquifer III:** Fine sand and medium-fine sand

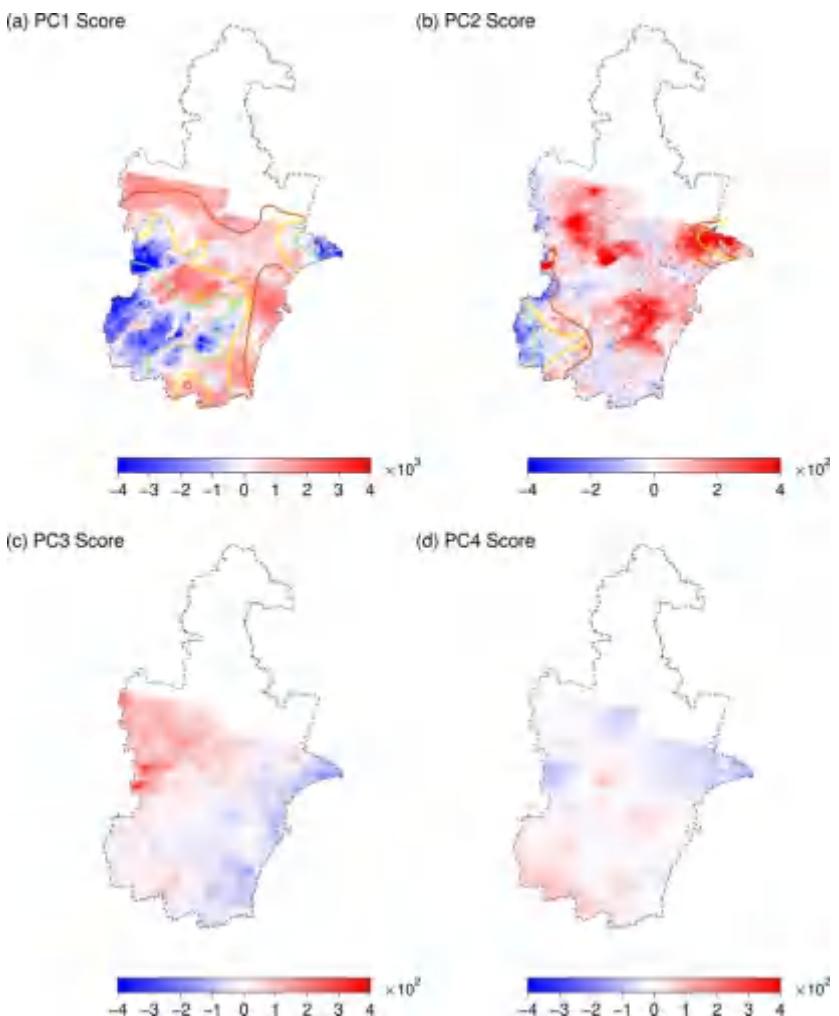
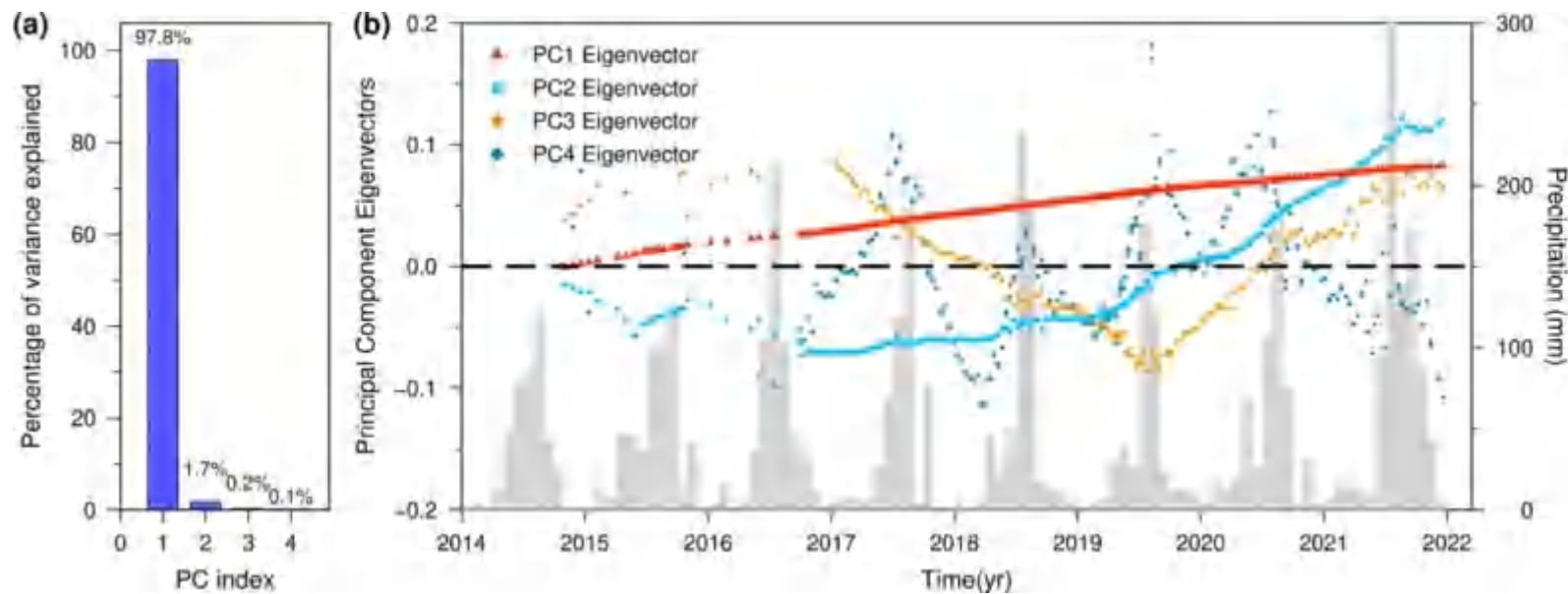
**Aquifer IV:** Medium-fine sand and fine sand

**Aquifer V:** Upper part: mud/sand interbeds  
Lower part: mud with a little silty and fine sand



# 京津冀地面沉降

## 主成分分析 Principal Component Analysis 特征值和特征向量



各主成分关联性

PC1  
第三含水层沉降

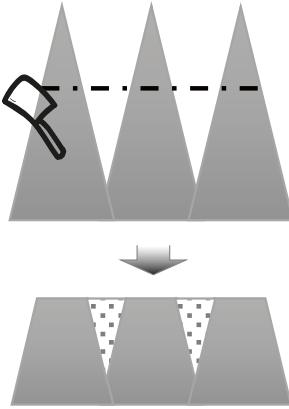
PC2  
第二含水层沉降

PC3  
含水层厚度

PC4  
季节性降水



山体滑坡  
粘塑性滑坡  
水电站边坡  
热融滑塌陷

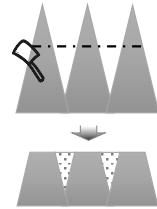


地面沉降  
地下水开采  
削山造城  
煤矿开采



地震震损

# 陕西省延安平山造城

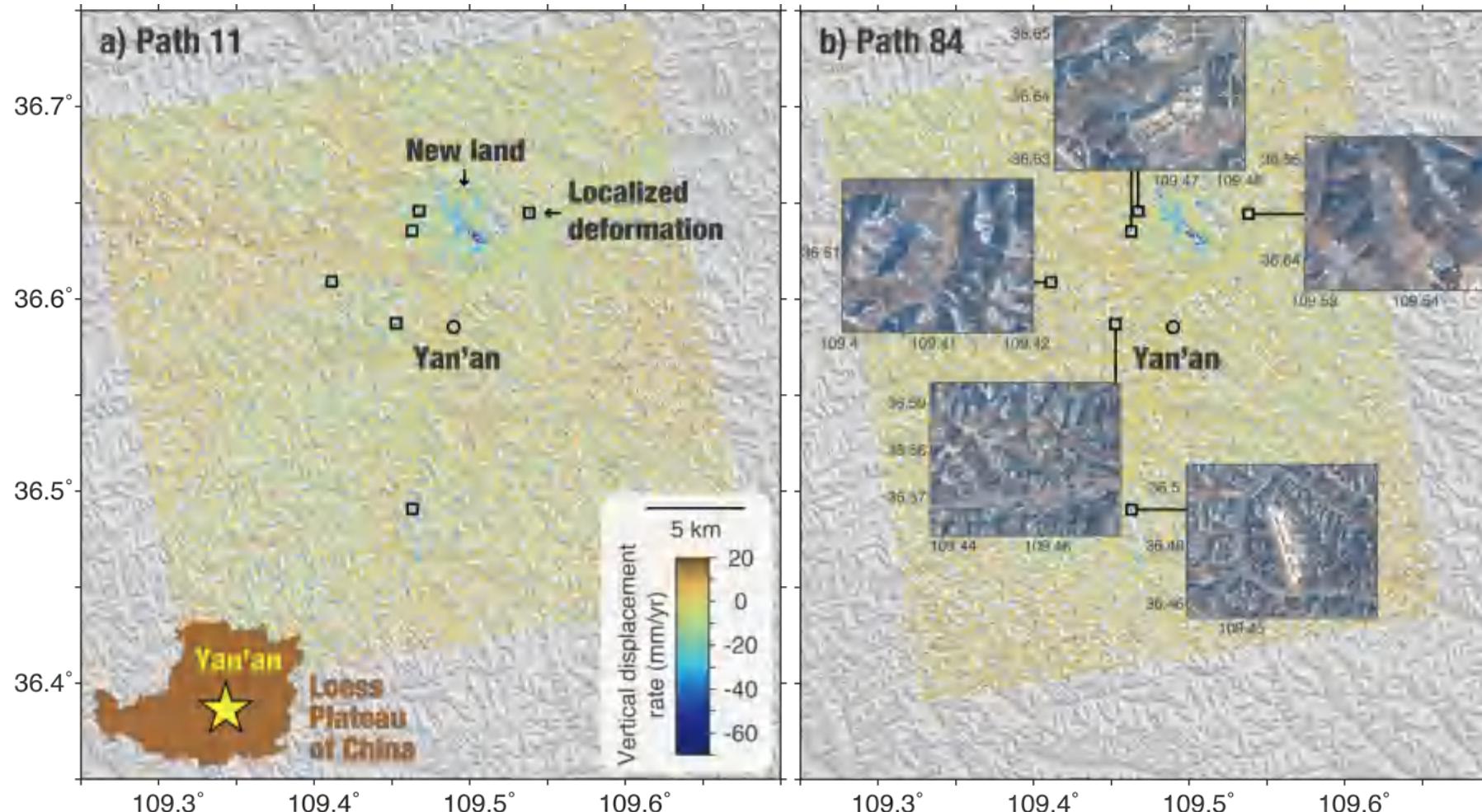


- 2012年4年起，10年打造78.5 km<sup>2</sup>延安新区
- 削山、填沟、造地、建城——地表手术



# 陕西省延安平山造城

## 2014-2020年欧空局哨兵一号卫星视线向形变场



- 六个局部形变区在两个轨道中均出现了超过40 mm/yr形变

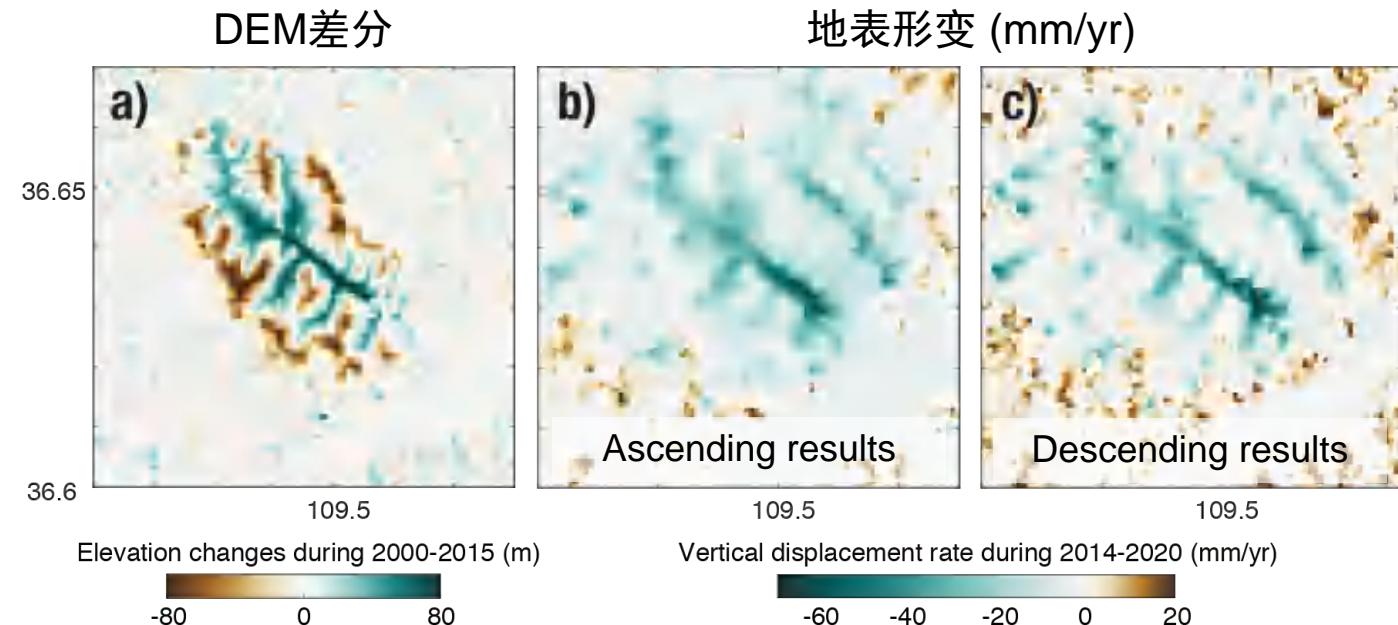
# 陕西省延安平山造城

地表手术

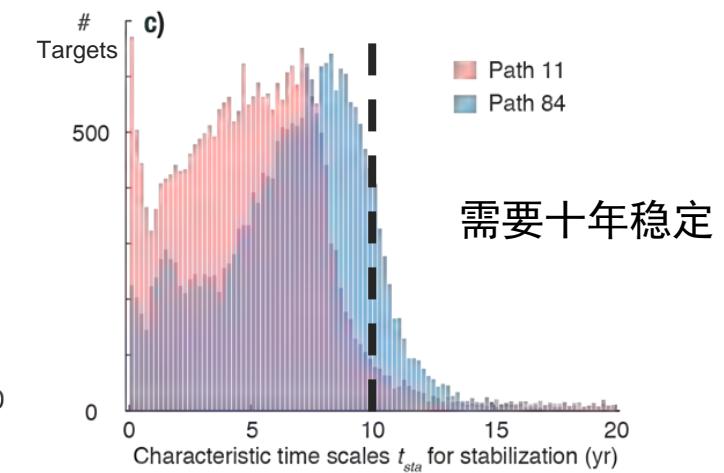
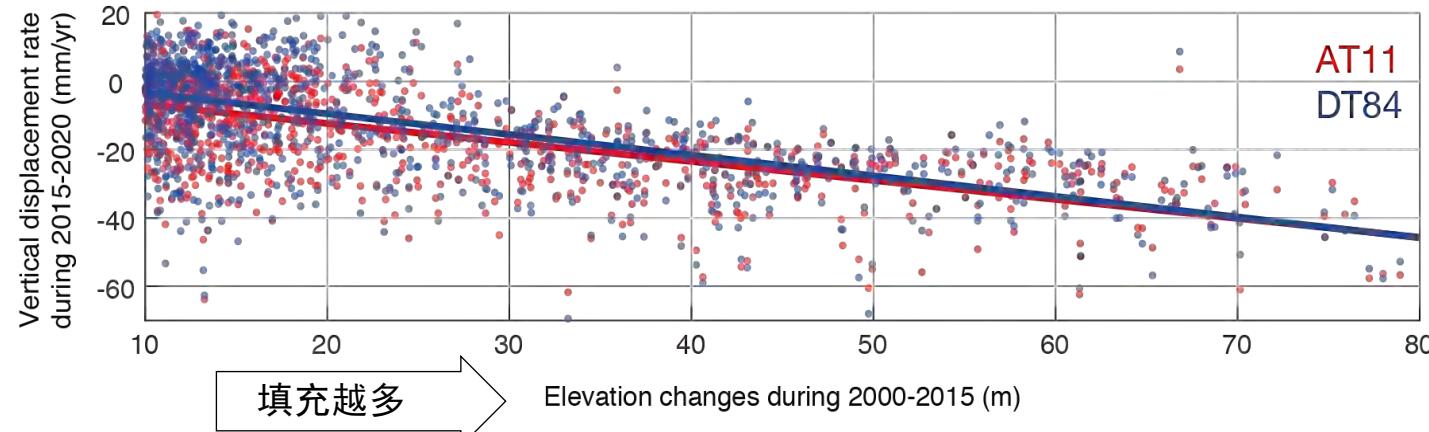


$1.28 \times 10^8 \text{-m}^3$  体积迁移

DEM差分

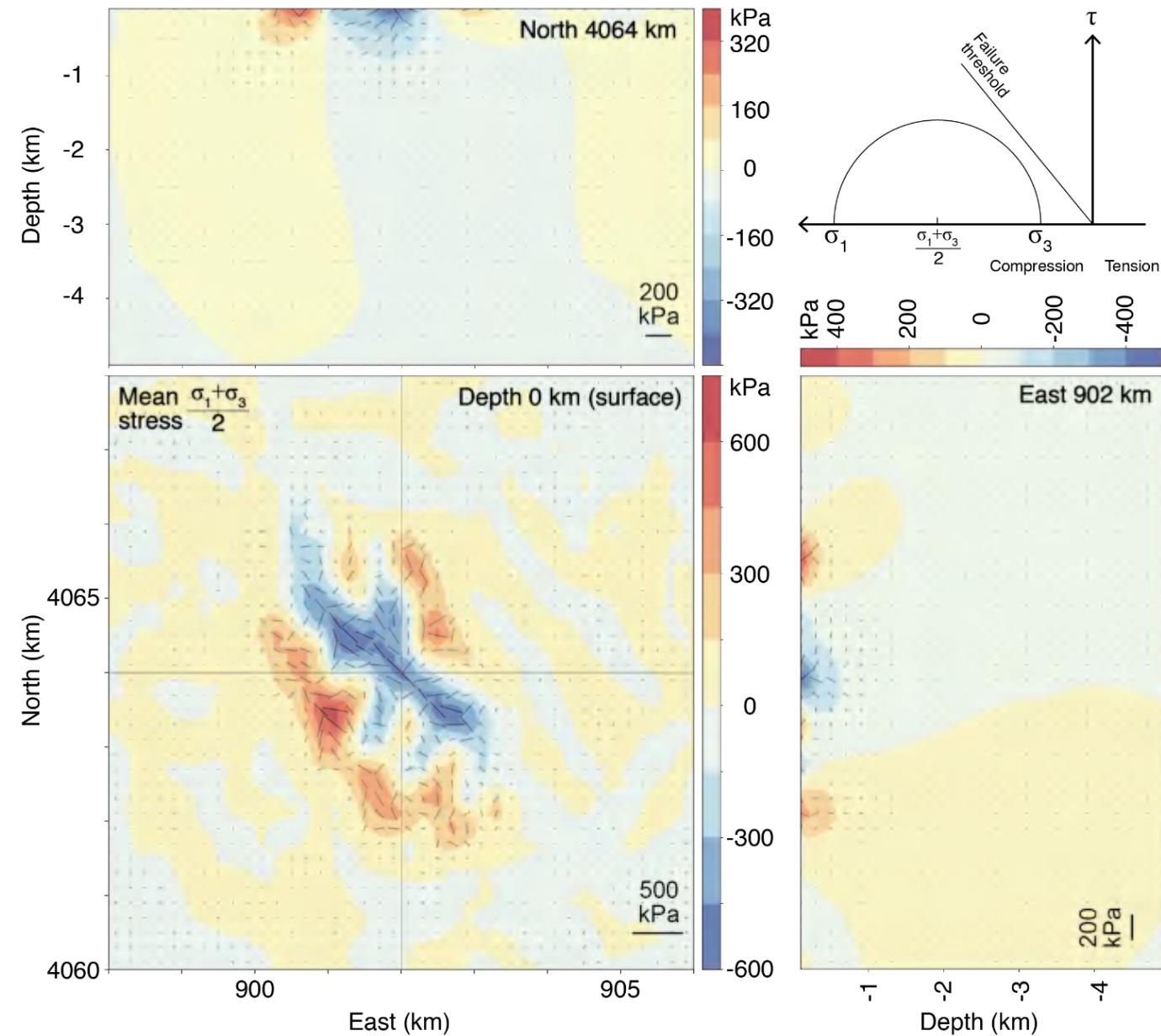


↓  
沉降速率越大



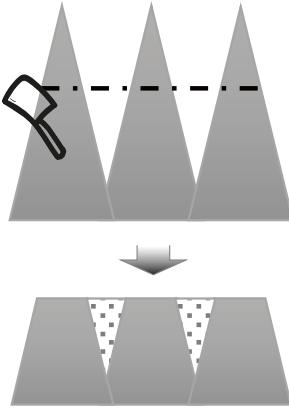
# 陕西省延安平山造城

- 地表应力
  - ~600-kPa compressive stress (-) over the elongated gully fills
  - ~650-kPa tensile stress (+) over the hill cuts at sides.
  
- 应力随着深度迅速变小，从四公里以下量级衰减到不足5 kPa
  - ~600 kPa at surface
  - ~100 kPa at 0.5-km depth
  - ~30 kPa at 1-km depth
  - ~10 kPa at 2-km depth
  - ~5 kPa at 4-km depth





山体滑坡  
粘塑性滑坡  
水电站边坡  
热融滑塌陷



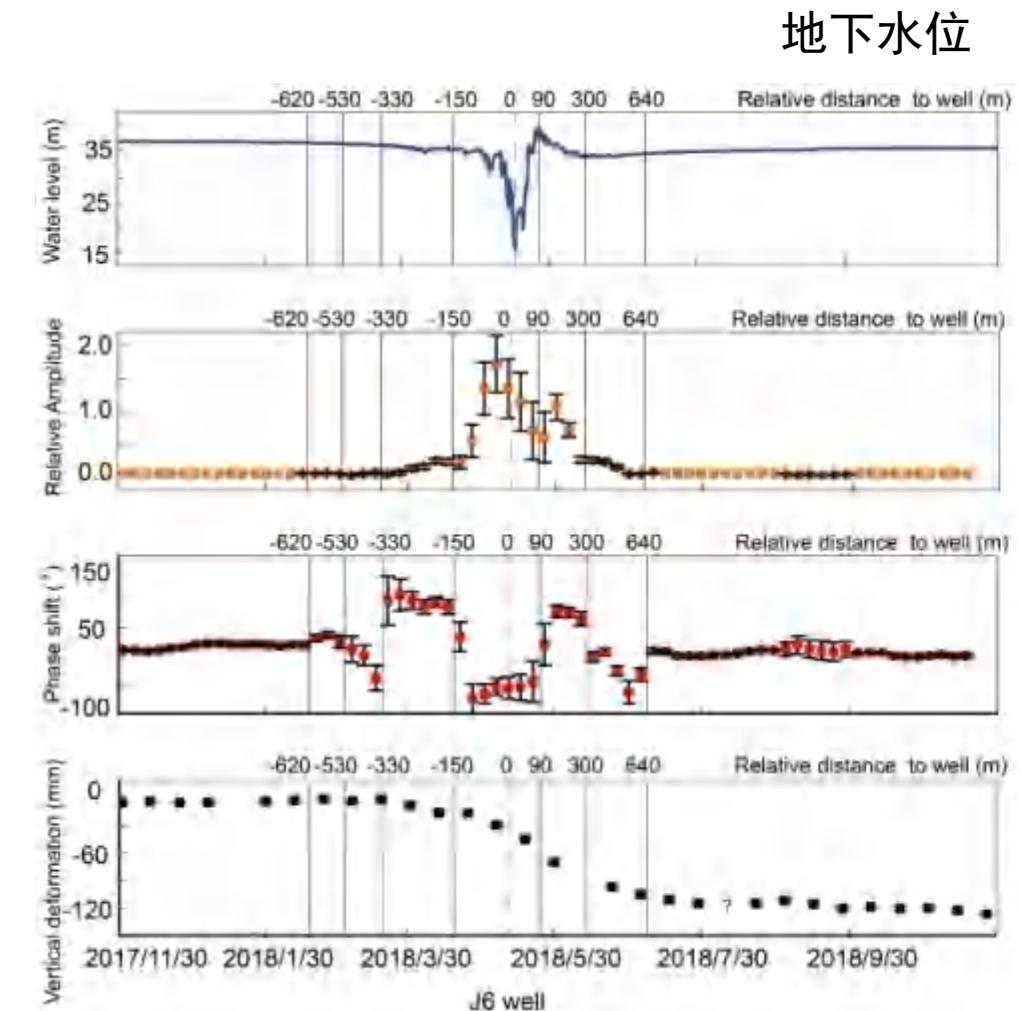
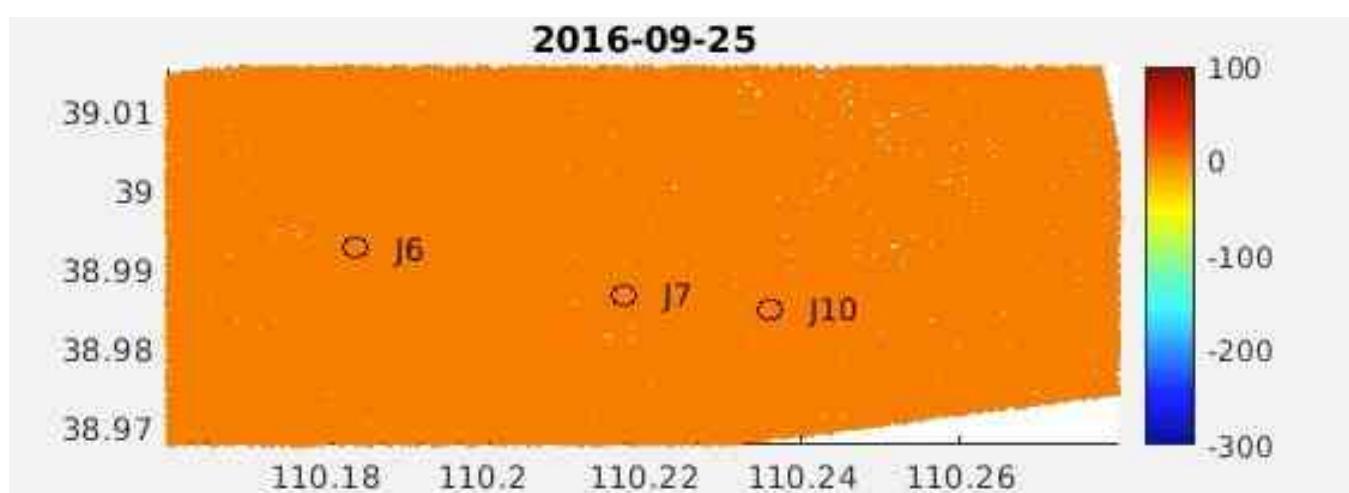
地面沉降  
地下水开采  
削山造城  
煤矿开采



地震震损

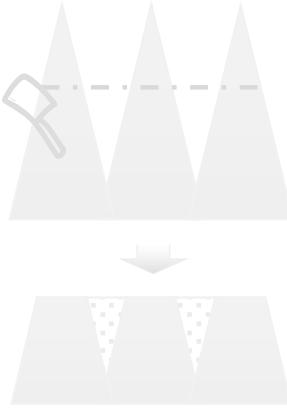
# 陕西省榆林矿区

- 动态监测采煤掘进过程，辅助风险评估
- 地下水异常→恢复，含水层破裂→应力释放→愈合





山体滑坡  
粘塑性滑坡  
水电站边坡  
热融滑塌陷

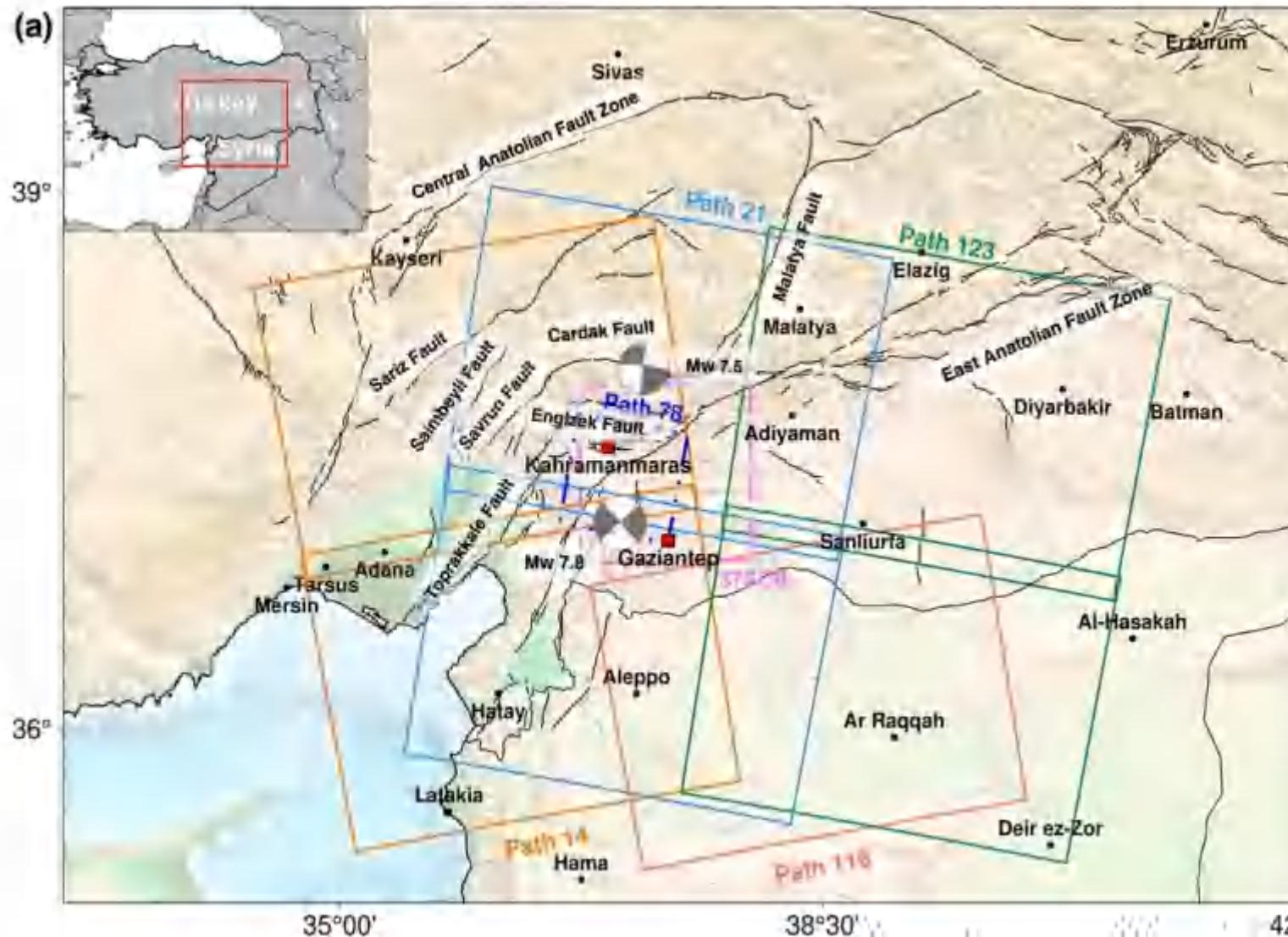


地面沉降  
地下水开采  
削山造城  
煤矿开采



**地震震损**

# 2023年土耳其-叙利亚地震建筑物震损评估

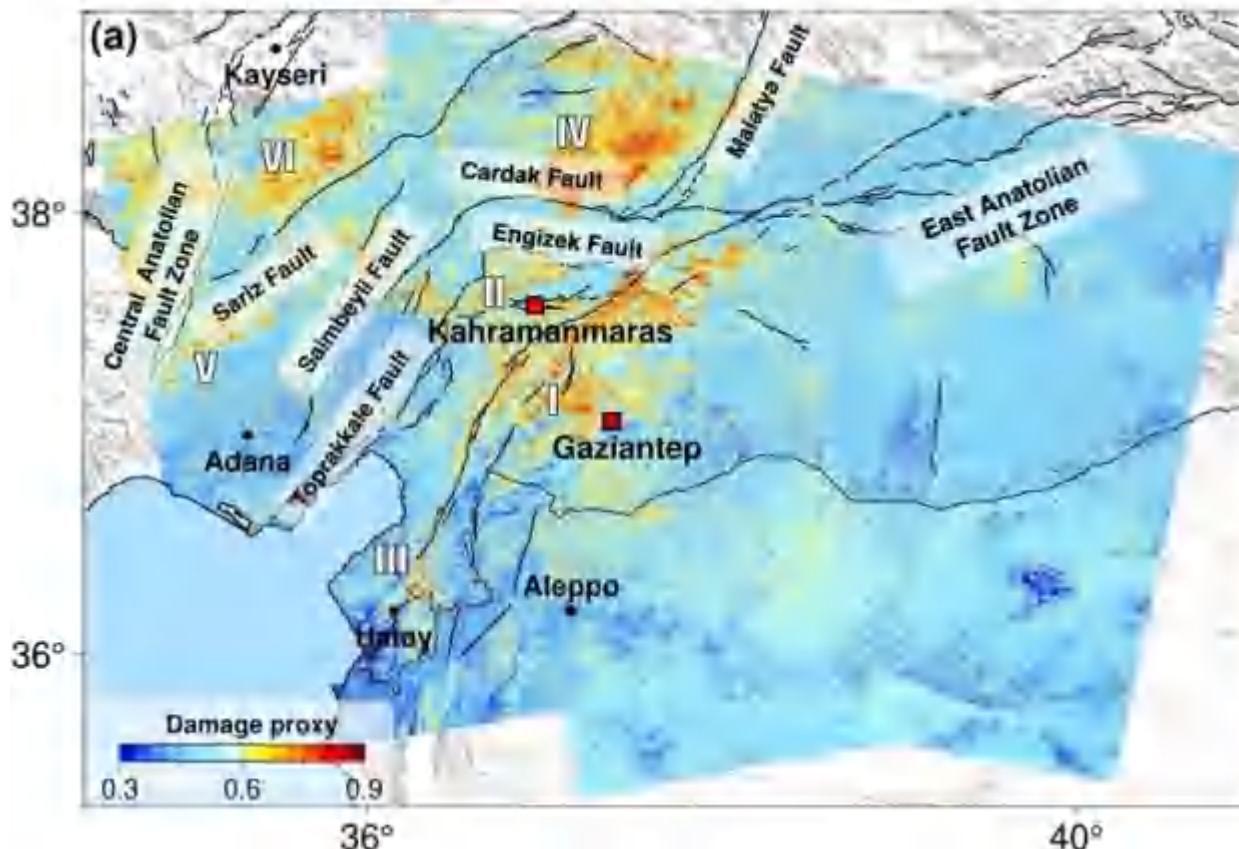


- 主震 2/6/2023 Mw7.8
- 余震 <12 h Mw7.6
- 44k死亡、160k建筑损毁

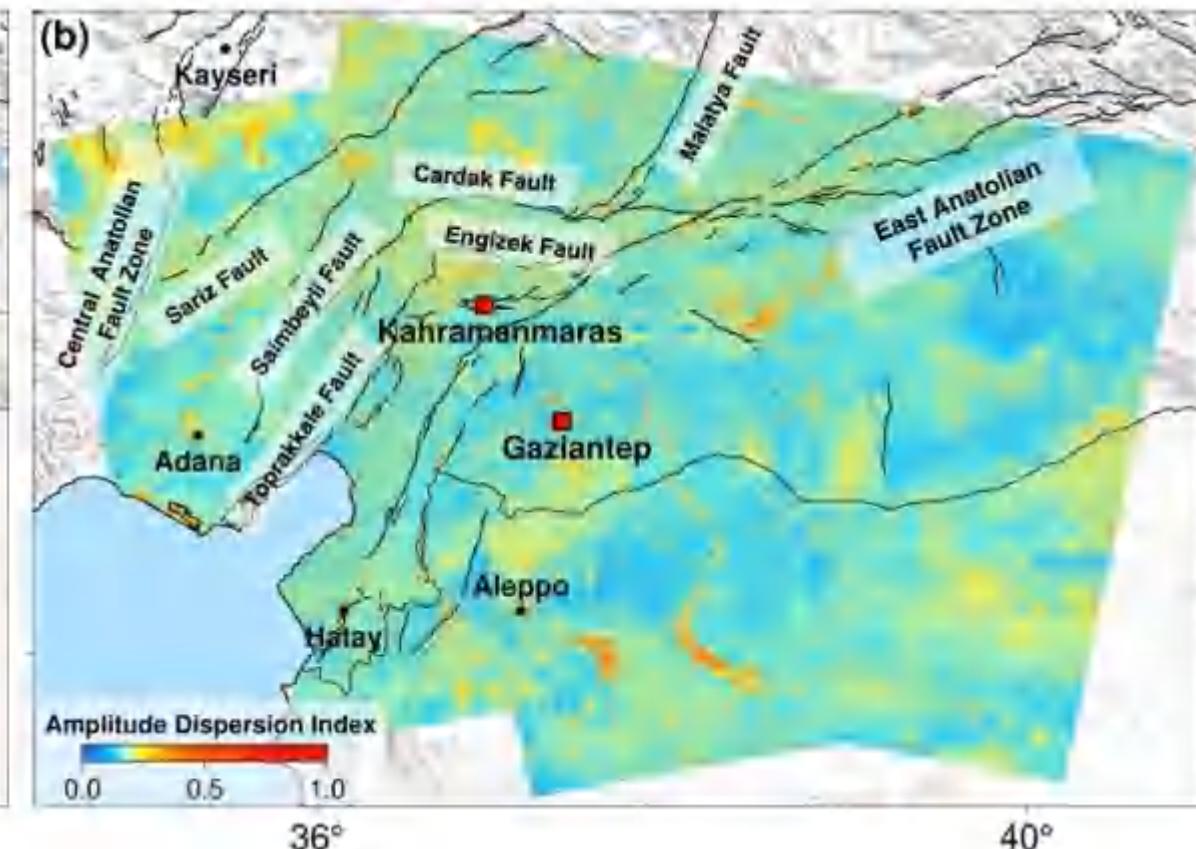
# 2023年土耳其-叙利亚地震建筑物震损评估

Sentinel-1 哨兵一号 SAR影像

$$\text{Damage proxy (DP)} \quad \gamma = \frac{|E(s_1 s_2^*)|}{\sqrt{E(|s_1|^2)} \sqrt{E(|s_2|^2)}} - \frac{|E(s_2 s_3^*)|}{\sqrt{E(|s_2|^2)} \sqrt{E(|s_3|^2)}}$$



$$\text{Amplitude dispersion index} \quad D_A = \frac{\sigma_a}{\bar{a}}$$

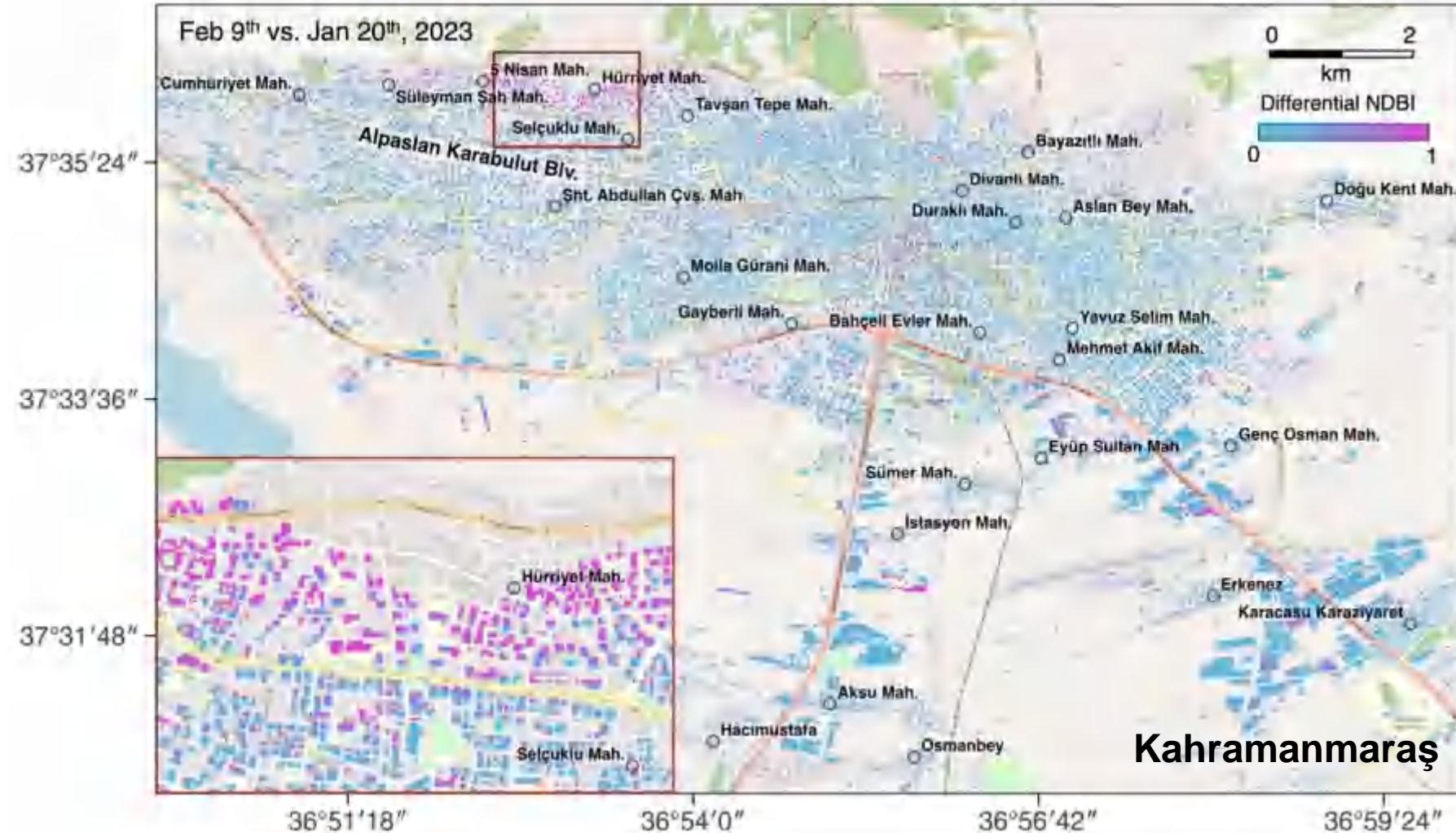


# 2023年土耳其-叙利亚地震建筑物震损评估

Sentinel-2 哨兵二号 光学影像

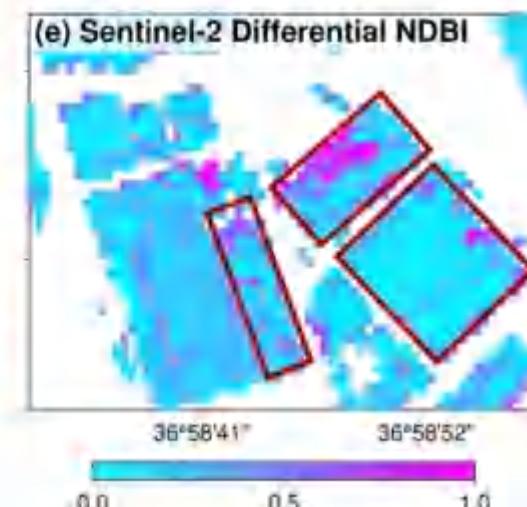
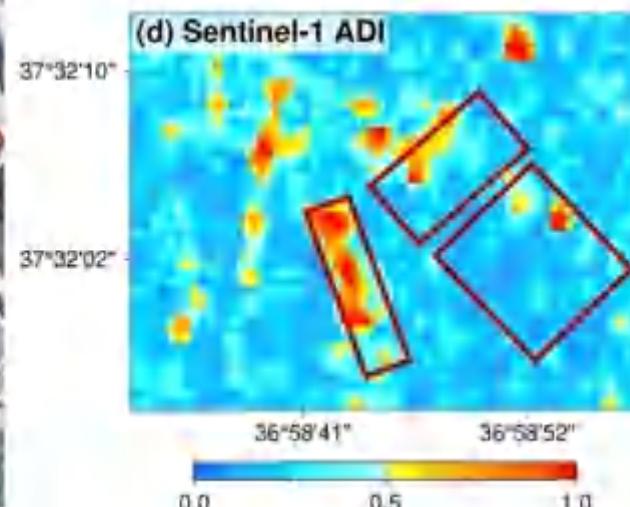
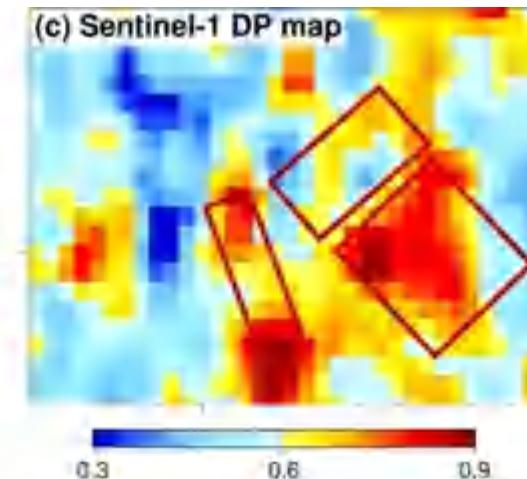
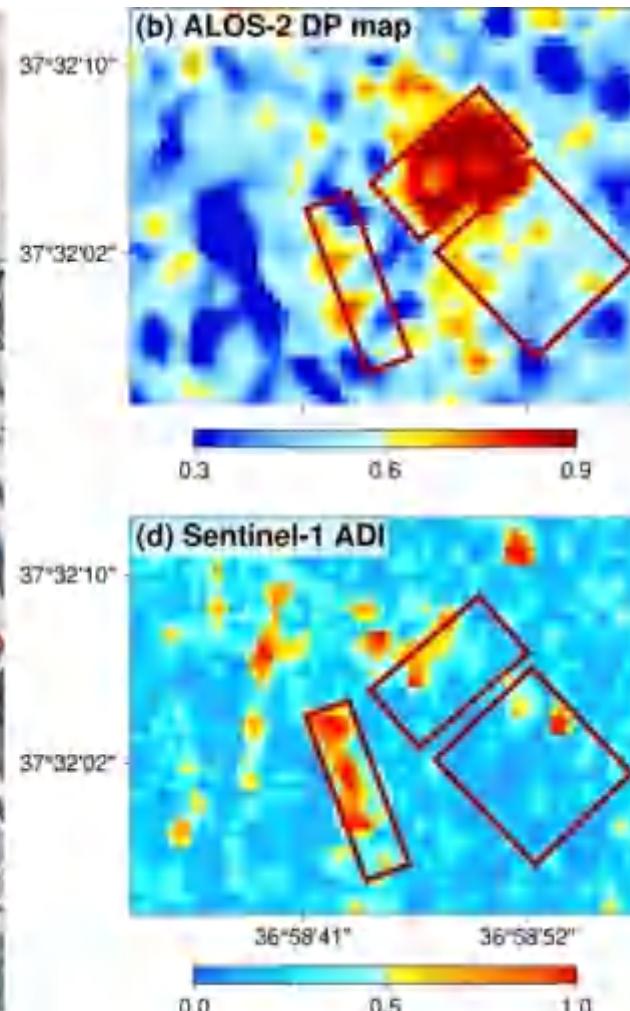
Normalized Differential Built-up Index (NDBI)

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$

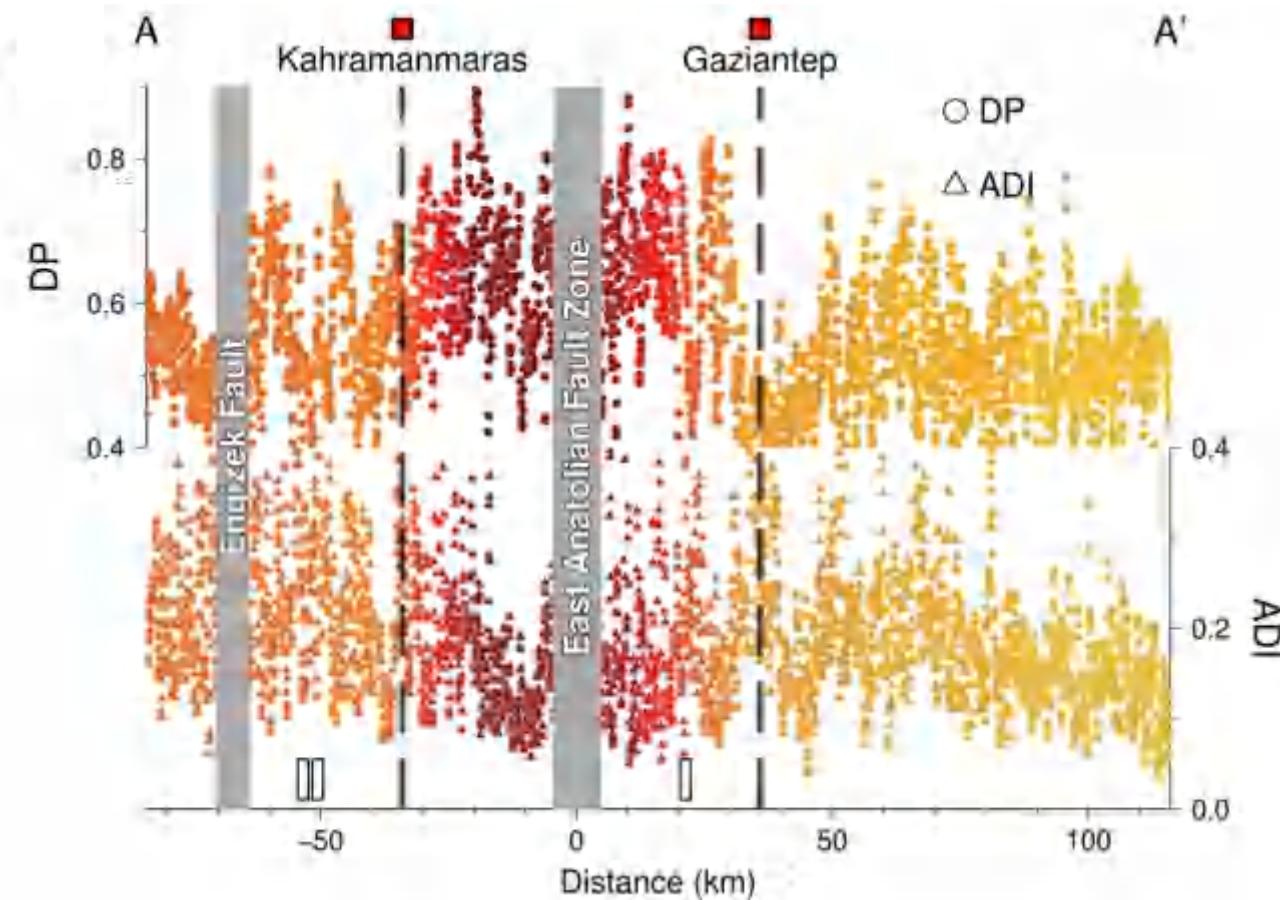


# 2023年土耳其-叙利亚地震建筑物震损评估

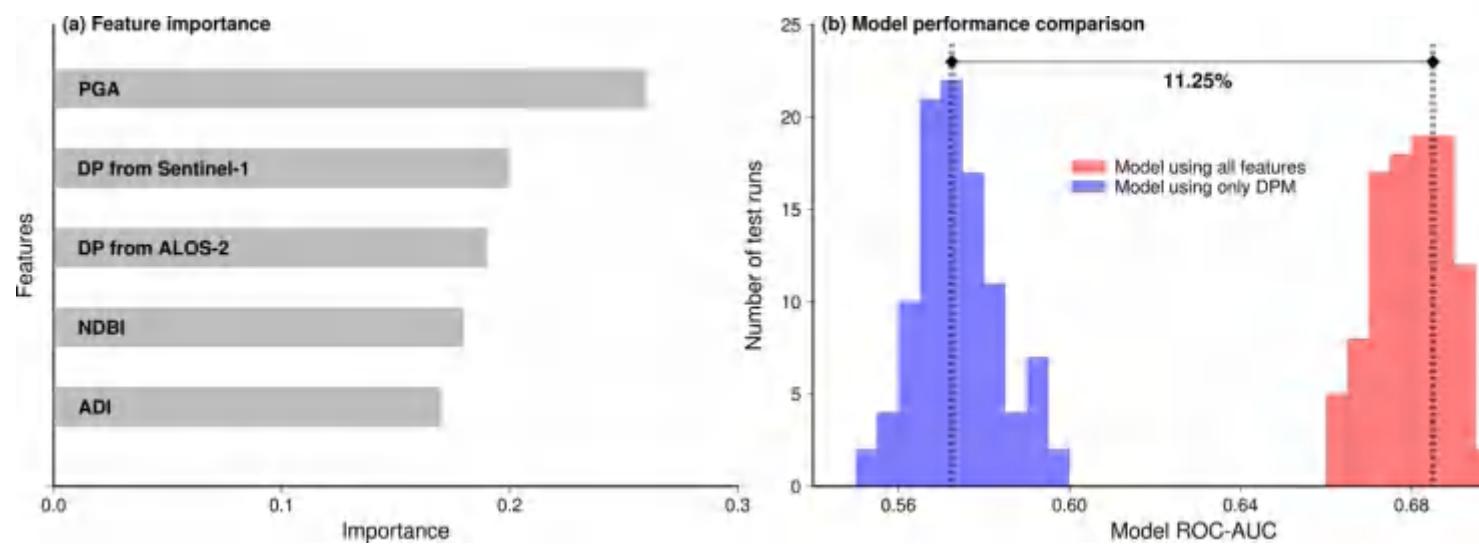
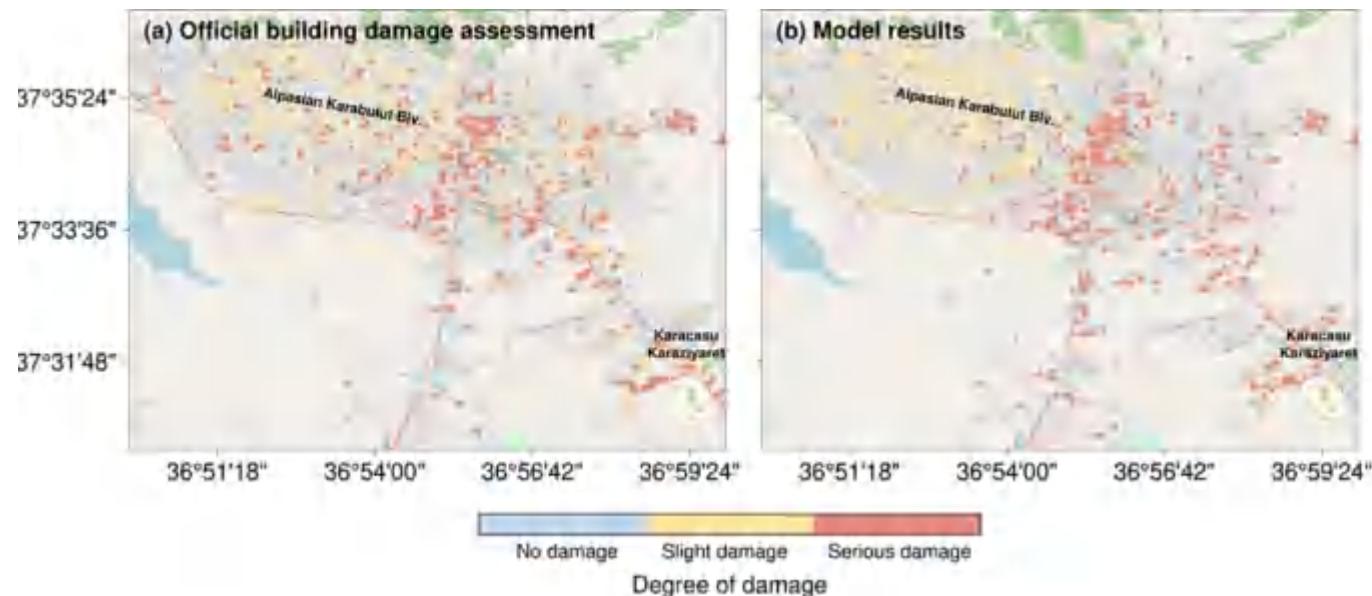
Damage proxy (DP) | Amplitude dispersion index (ADI) | Normalized Differential Built-up Index (NDBI)



# 2023年土耳其-叙利亚地震建筑物震损评估



# 2023年土耳其-叙利亚地震建筑物震损评估



Yukarıda gösterilen haritayı oluşturmak için (Suzu Yu, PhD (State University of New York at Albany), Ali Hu, PhD (Tsinghua University), Han Young Noh, PhD (Stanford University) ve Xilei Zhao, PhD (University of Florida)) tarafından hazırlanan orijinal çalışma (ayrıca [burada](#)) kullanılmıştır.

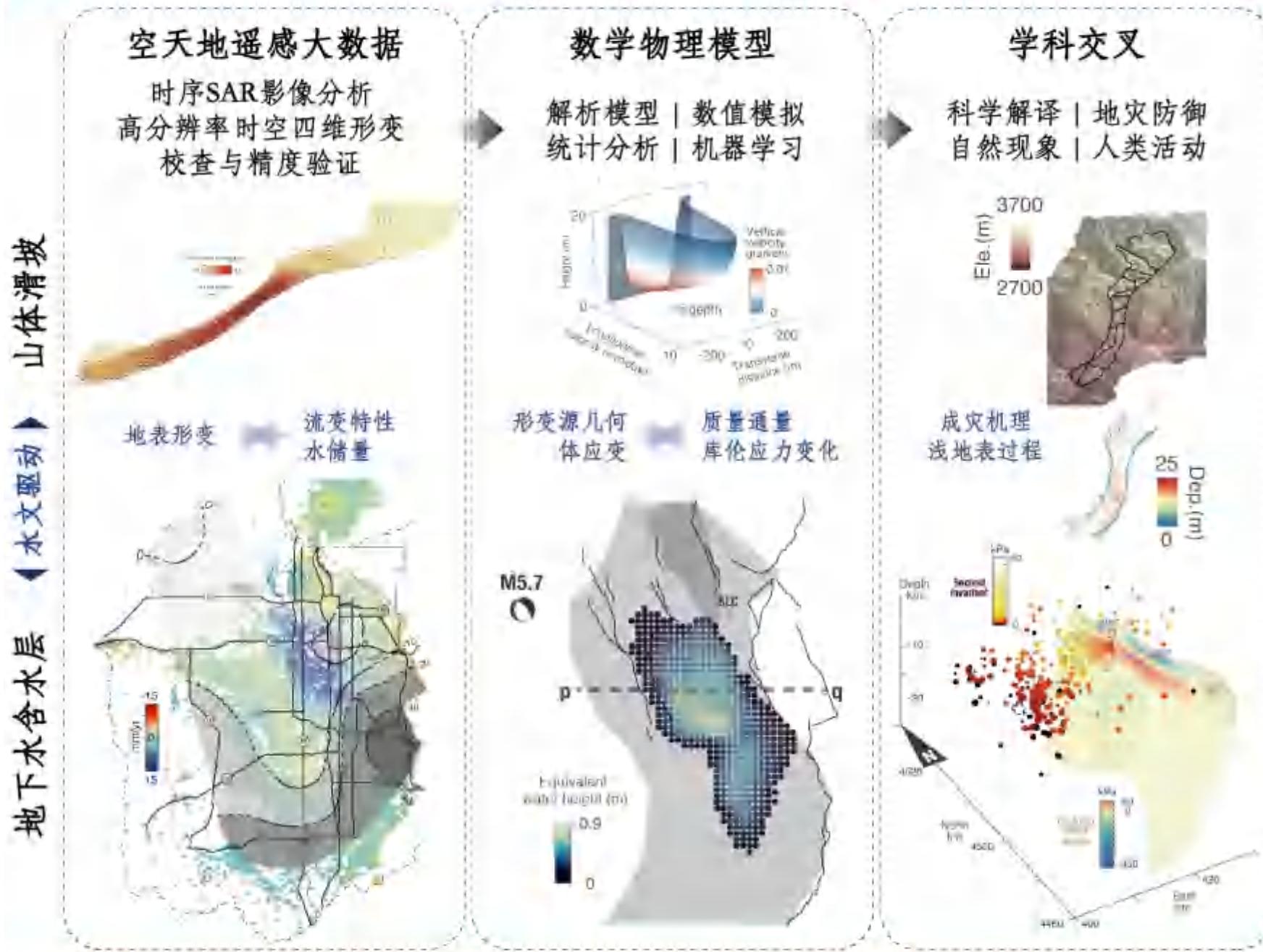
(The data used in creating the above map was obtained from the work of Suzu Yu, PhD (State University of New York at Albany), Ali Hu, PhD (Tsinghua University), Han Young Noh, PhD (Stanford University), and Xilei Zhao, PhD (University of Florida). You can access the original study by clicking [here](#).)

Talimci Hasarlı Bina Haritası



<https://afetharitasi.org/>

主震15天后，结果被土耳其政府组织采用  
The Turkish earthquake information platform funded by AFET PLATFORMU (Disaster Platform) and Turkish Philanthropy Funds





北京大学  
PEKING UNIVERSITY



谢谢！

地质灾害与浅表过程遥感课题组

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