

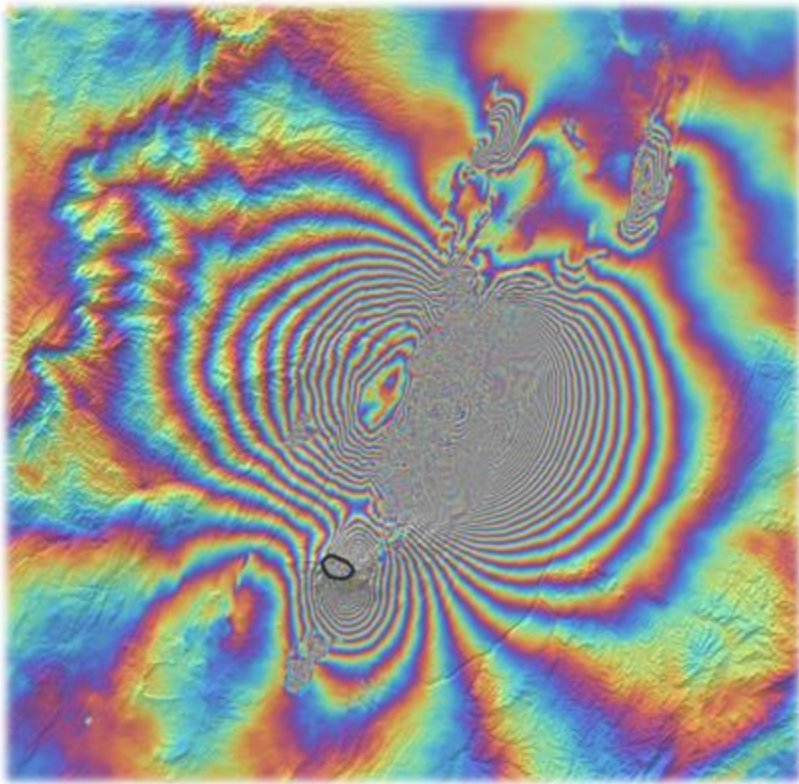
Synergistic Use of Multi-Mission SAR Interferometry for Imaging Rapid Deformation: The 2024–2025 Fentale-Dofen Magma Intrusion

Weiyu Zheng¹, Juliet Biggs¹, Lin Way¹, Edna Dualeh¹, Simon Orrego¹, Milan Lazecky², Raphael Grandin³, Marco Bagnardi⁴
¹University of Bristol, ²University of Leeds, ³Institut de Physique du Globe de Paris, ⁴U.S. Geological Survey

Jun 17, 2026

Recent Dyke Intrusion Episodes

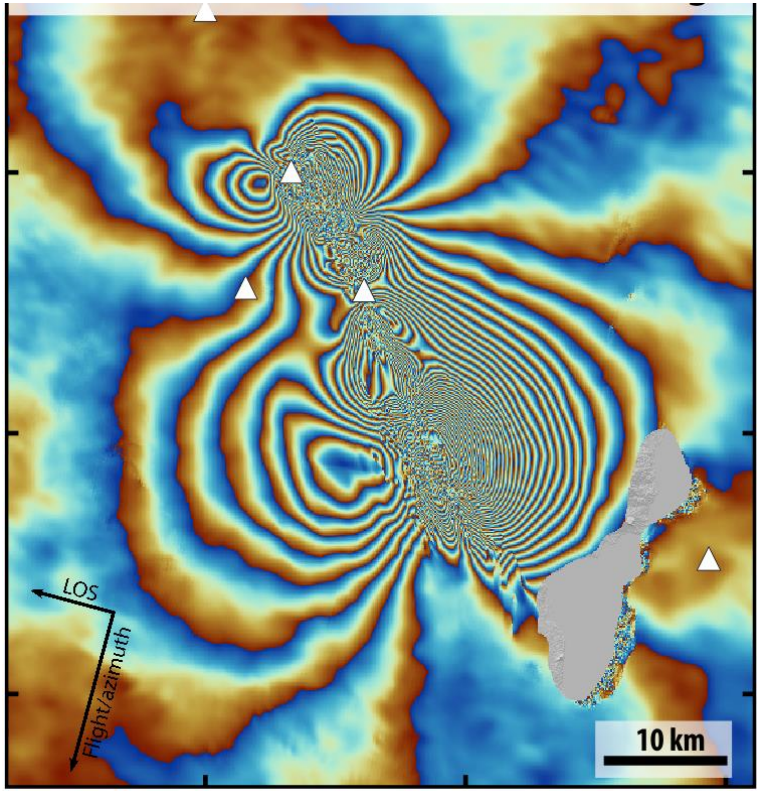
Fentale-Dofen (Ethiopia)
2024-5



>1 km³ over 3 months

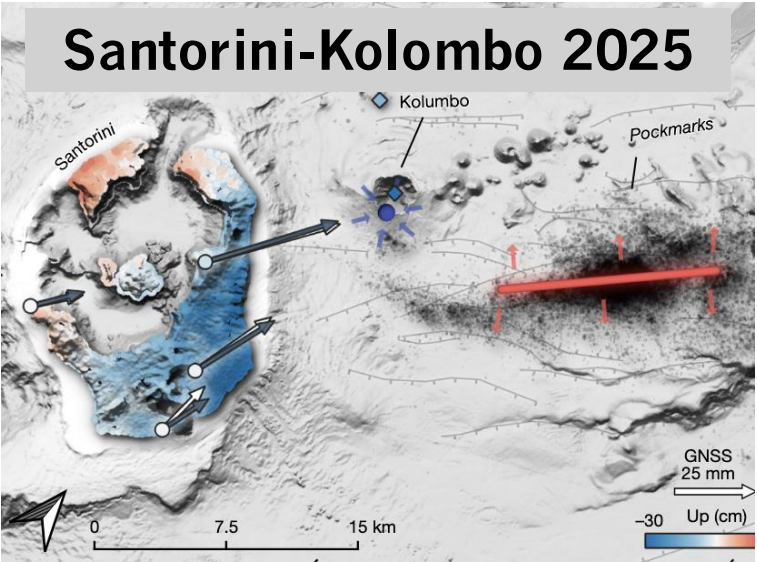
75,000 people evacuated
No local, real-time monitoring

Erte Ale (Ethiopia)
2025



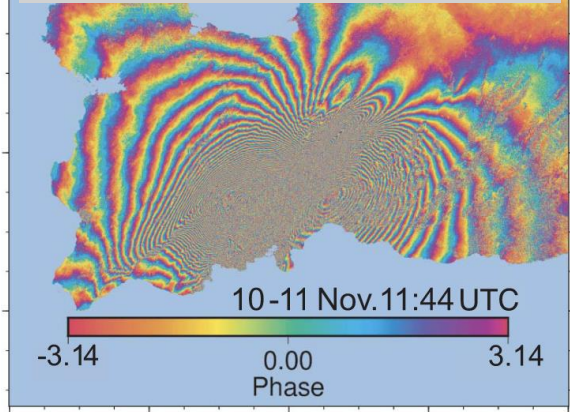
<0.4 km³ over 25 days

La Rosa et al 2025



0.31 km³ over 1 month

Svartsengi, Iceland
2023-2024

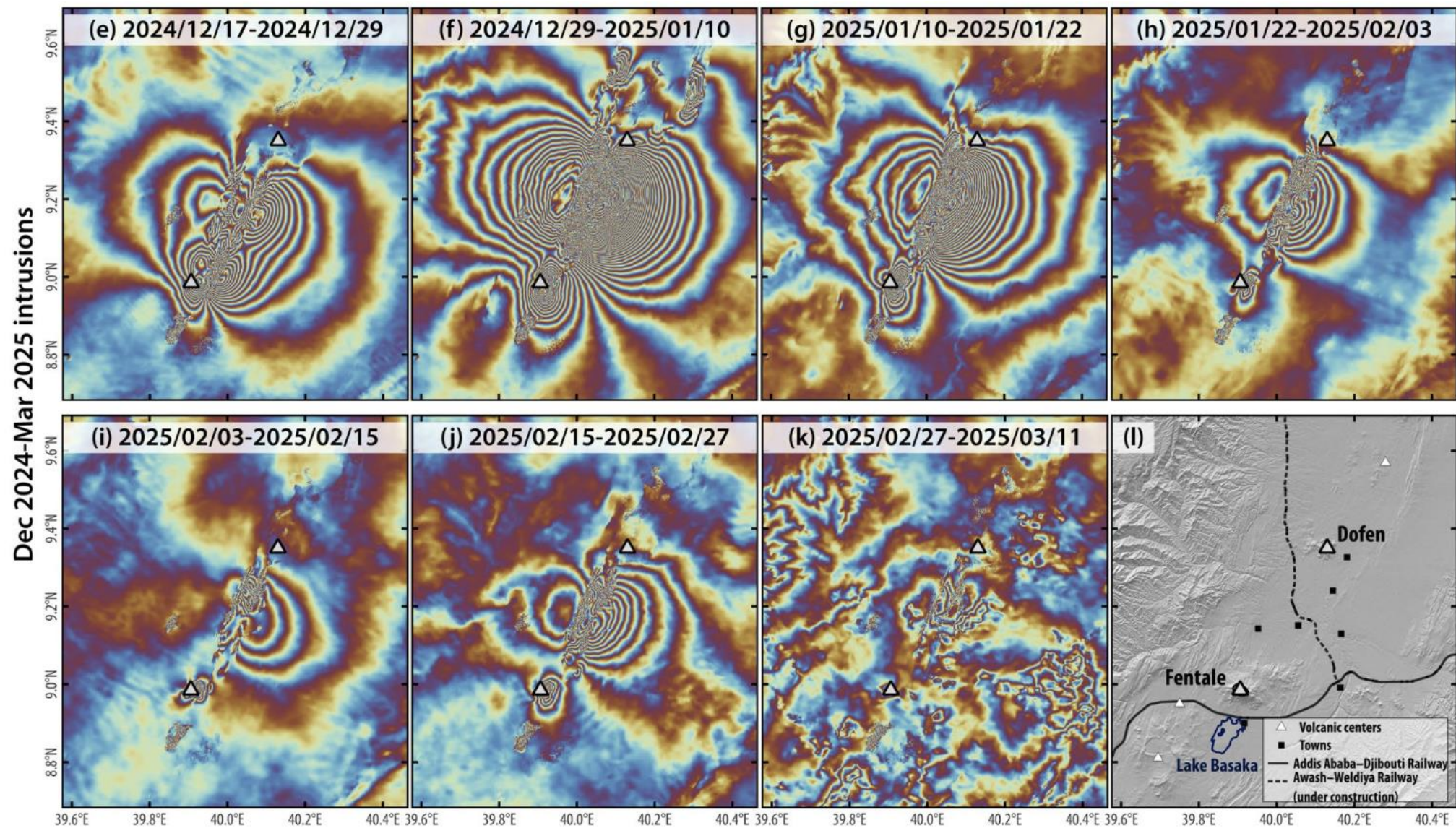


9 intrusions in 13 months
Each <15 hours and <0.133 km³

*Sigmundsson et al 2024,
Parks et al, 2025*

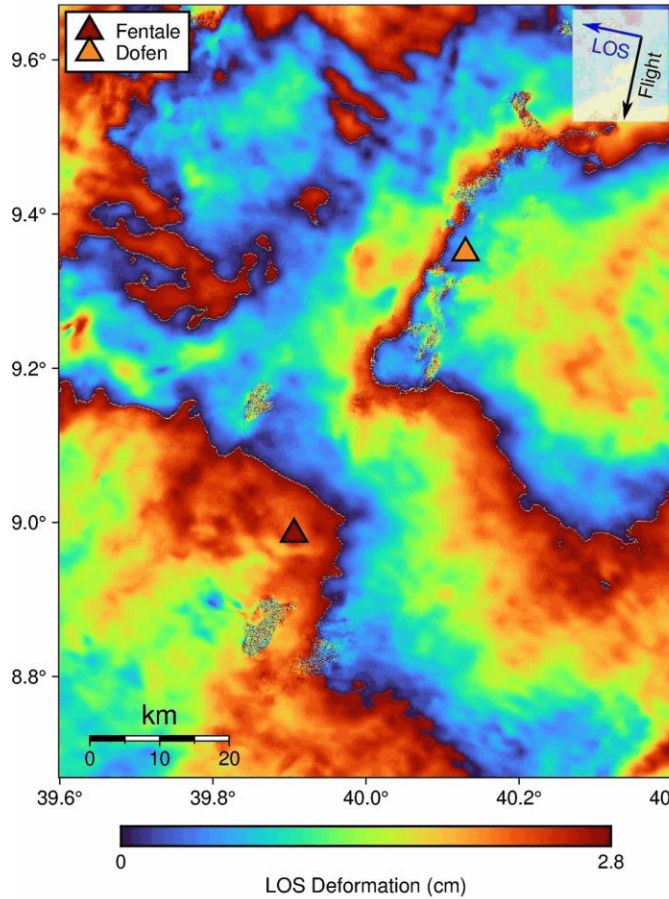
Isken et al 2025

Sentinel-1: Regional coverage; 12-day repeat (S1-A)

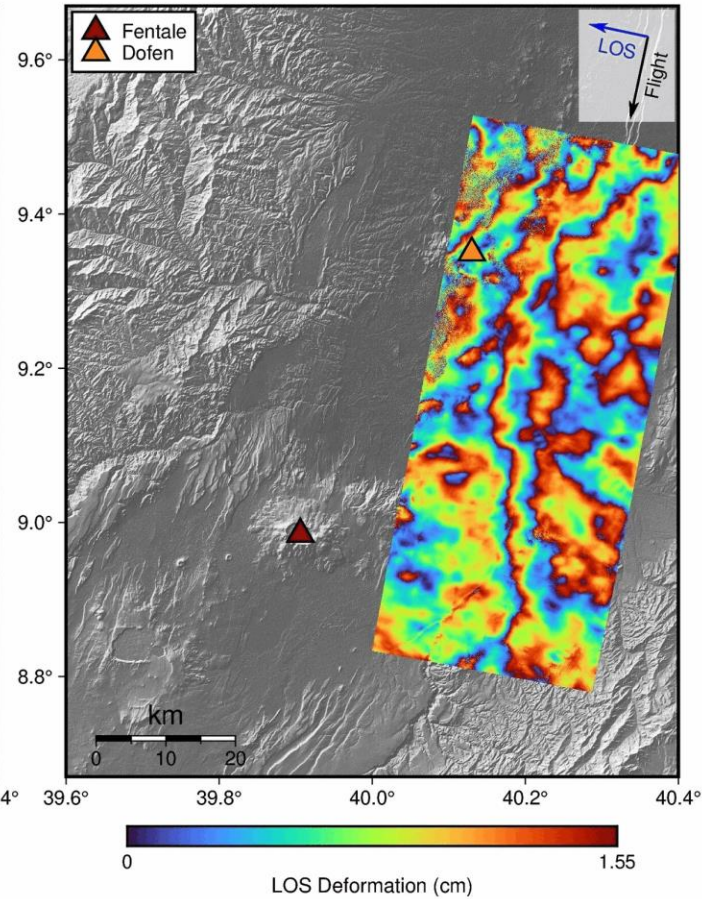


Multi Mission SAR Observations

Sentinel-1
20241205-20241217



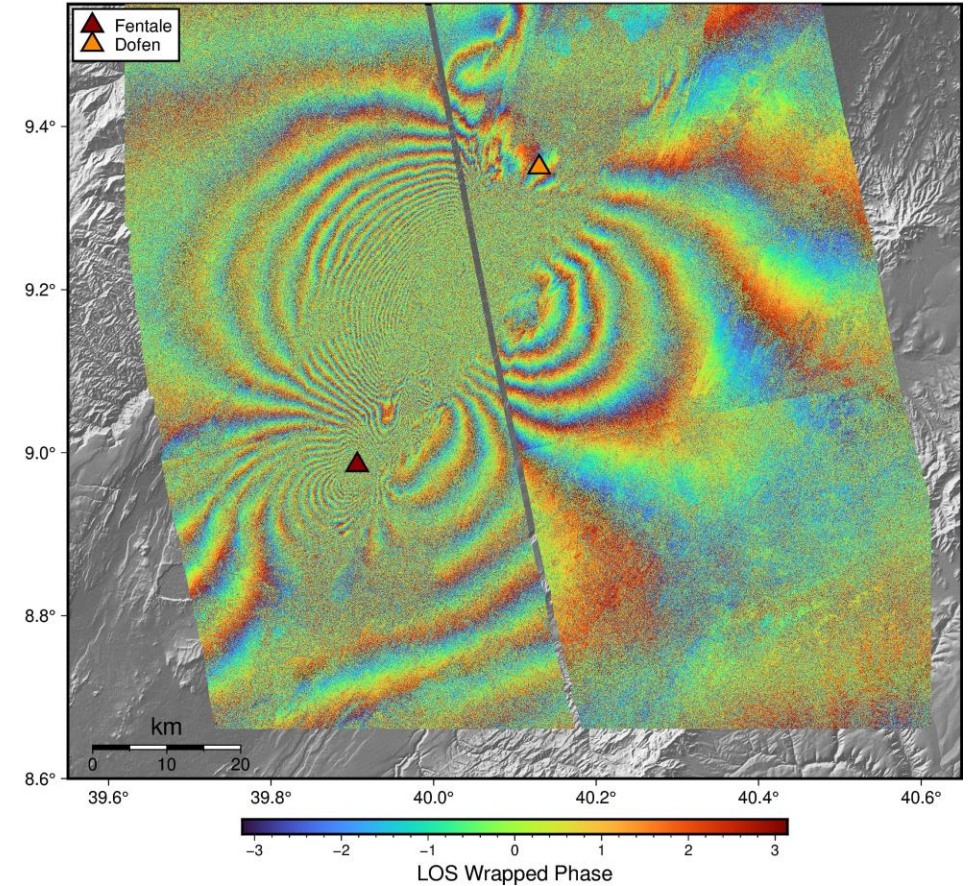
CSK
20241205-20241213



SAOCOM total deformation

Left: 2024/09/21-2025/07/06

Right: 2024/10/23-2025/05/03



Before the event

Real-time monitoring and response



**Starting Oct 2024:
Regular event reports on ongoing activity**

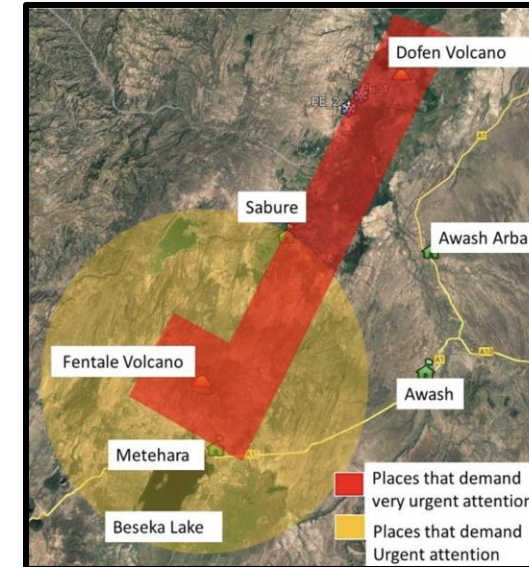
COMET Event Response Report 1.2

Issued 17.00 BST 22nd October 2024



Area of Interest: Fentale Volcano, Ethiopia
Date Covered: 8-22th October 2024
Authors: Juliet Biggs (Bristol), Lin Way (Bristol), Milan Lazecky (Leeds), Weiyu Zheng (Bristol), Tim Wright (Leeds), Andy Hooper (Leeds).

**Jan 2025: Hazard map from
Ethiopian scientific committee**

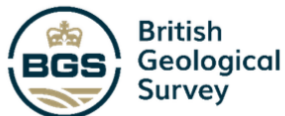


**75,000 people
evacuated**

**No magmatic
eruption**

Lewi et al 2025

**From Jan 2025:
Supported BGS' Volcano Advisories**



Volcano Advisory

Geological Assessment for Fentale-Dofen, Ethiopia, 13 January 2025

Headline: Evacuations and ongoing earthquakes, phreatic explosive venting, ground fissuring, potential for volcanic eruption.

Oct 2025: Published as a Data Report

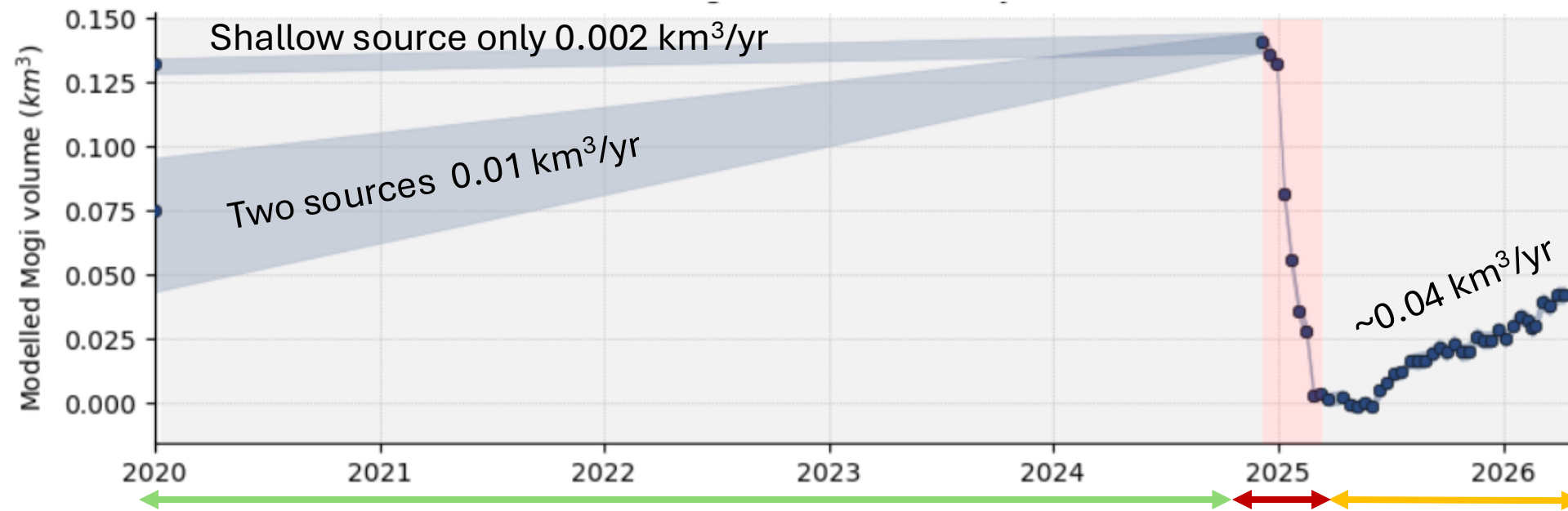
Bulletin of Volcanology (2025) 87:100
<https://doi.org/10.1007/s00445-025-01884-3>

DATA REPORT

Real-time satellite monitoring of the 2024–2025 dyke intrusion sequence at Fentale-Dofen volcanoes, Ethiopia

Lin Way¹ · Juliet Biggs¹ · Weiyu Zheng¹ · Milan Lazecky² · Edna W. Dualeh¹ · Tim Wright² · Raphaël Grandin³ · Arthur Hauck³ · Sue Loughlin⁴ · Julia Crummy⁴ · Elias Lewi⁵

What's next? Reinflation

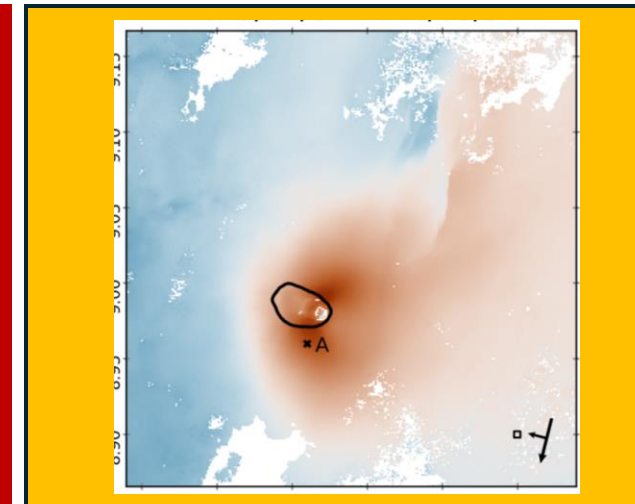
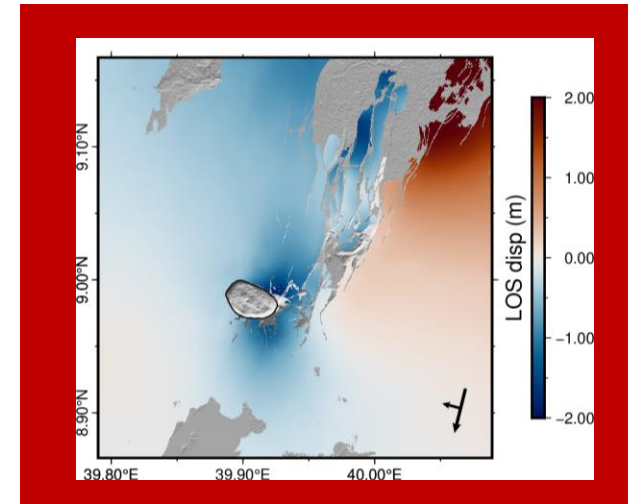
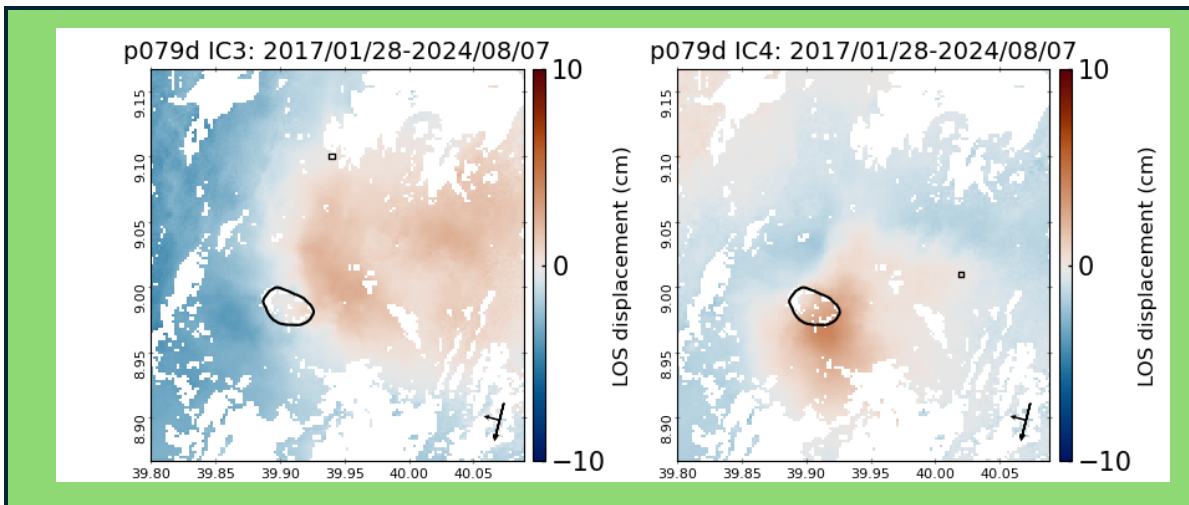


Way et al, in prep

Pre-intrusion

Co-intrusion

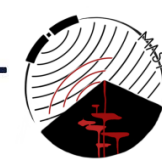
Post-intrusion



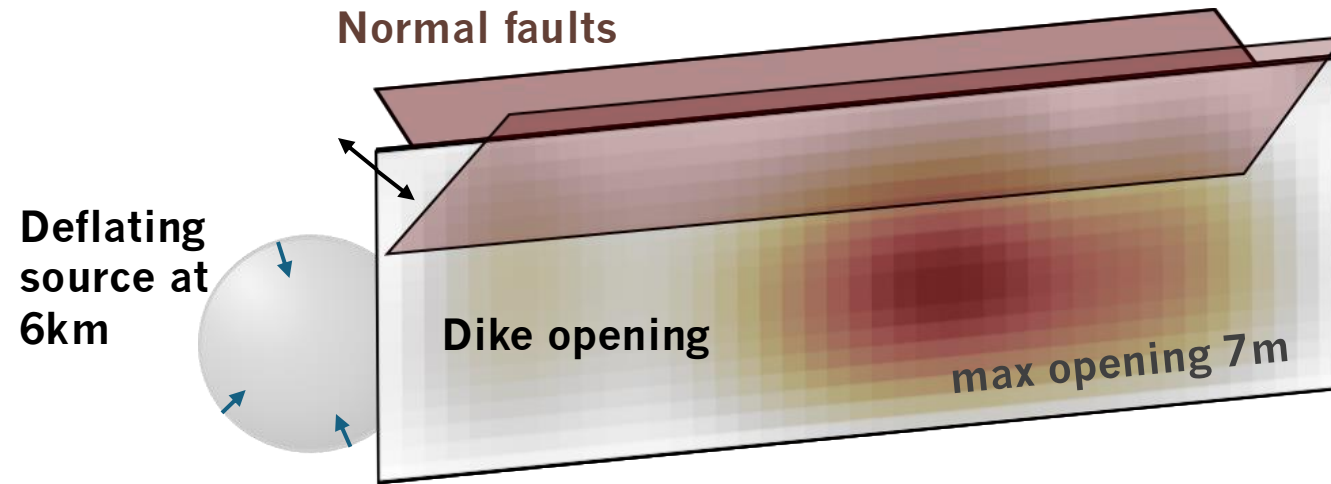
Kinematic Models



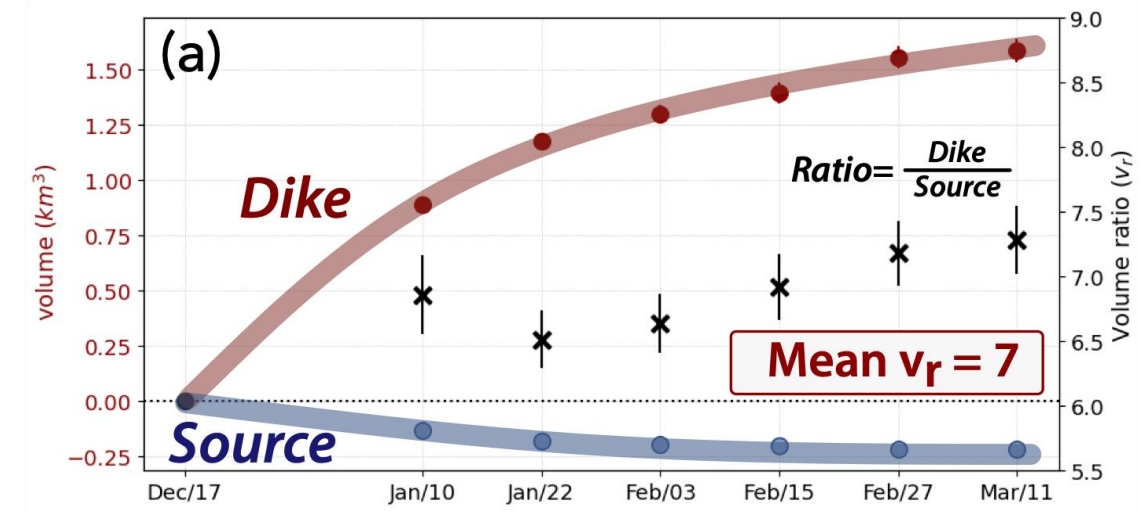
COMET



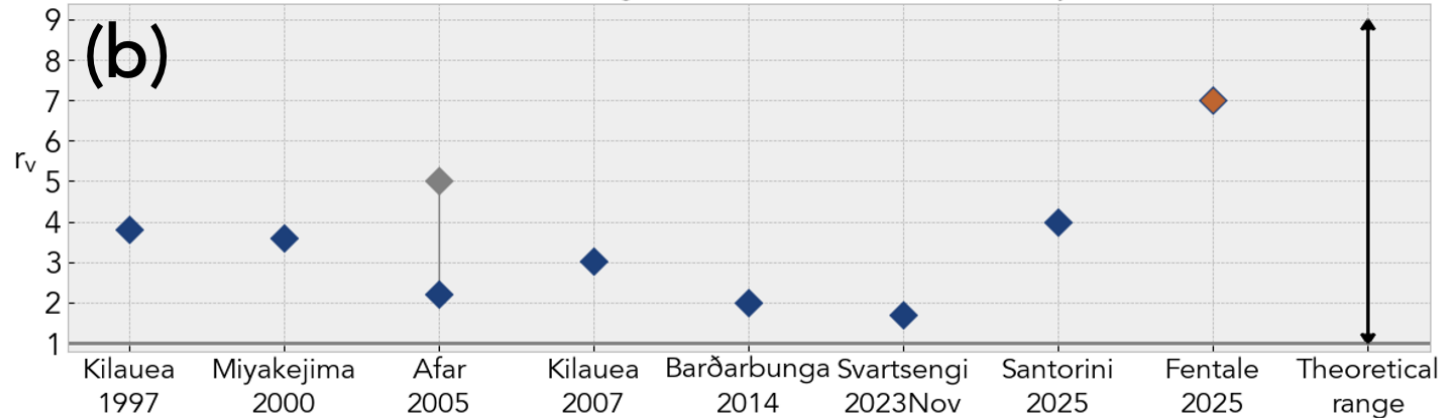
[1] Model set up



[2] Volume estimates



Intruded dike:deflating source volume ratios (r_v) at mafic systems



$$v_r = \frac{\Delta \text{volume}_{\text{dike}}}{\Delta \text{volume}_{\text{source}}} = 7$$

$$= 1 + \frac{\beta_m}{\beta_c}$$

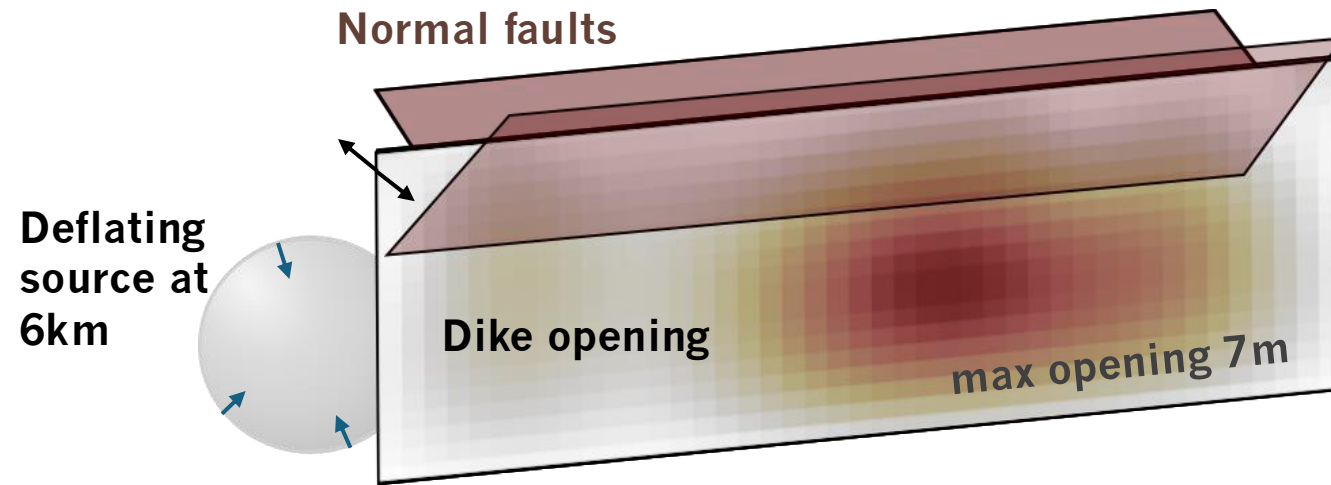
Kinematic Models



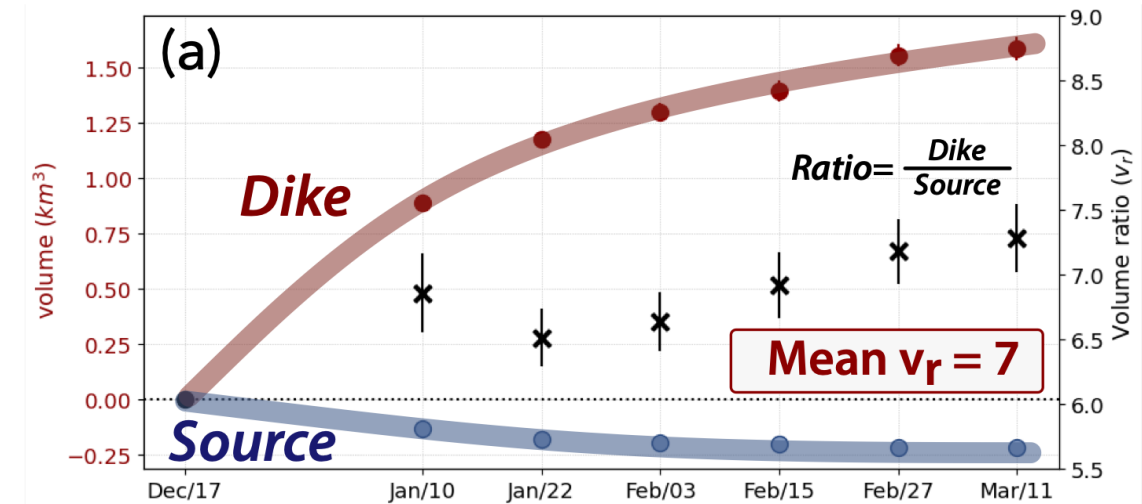
COMET



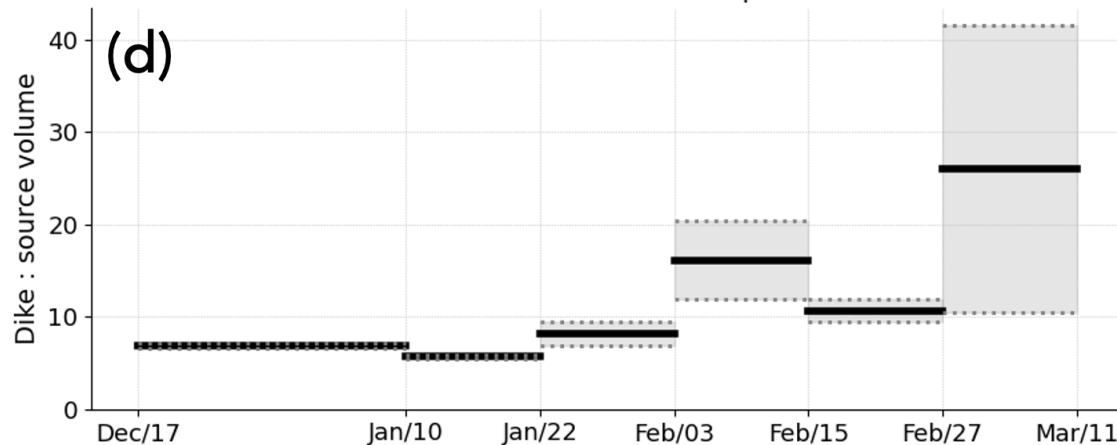
[1] Model set up



[2] Volume estimates



volume ratio for each time period

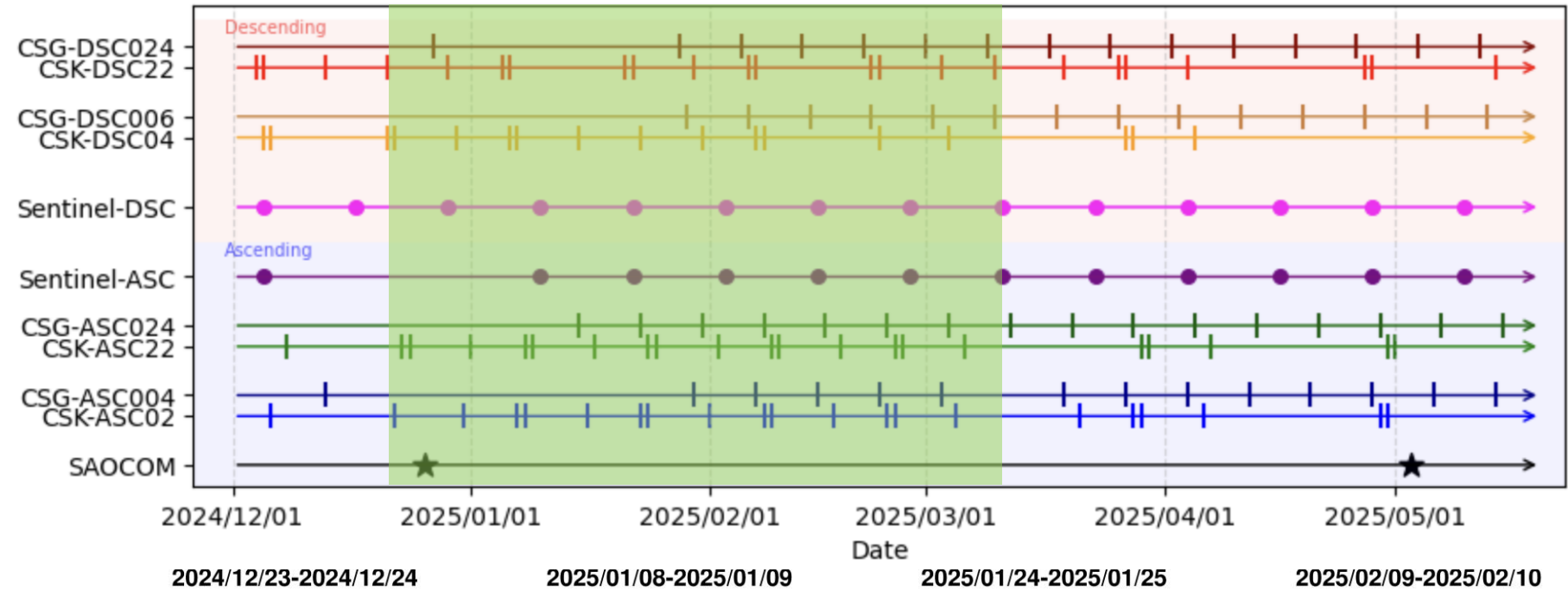


Possible Explanations:

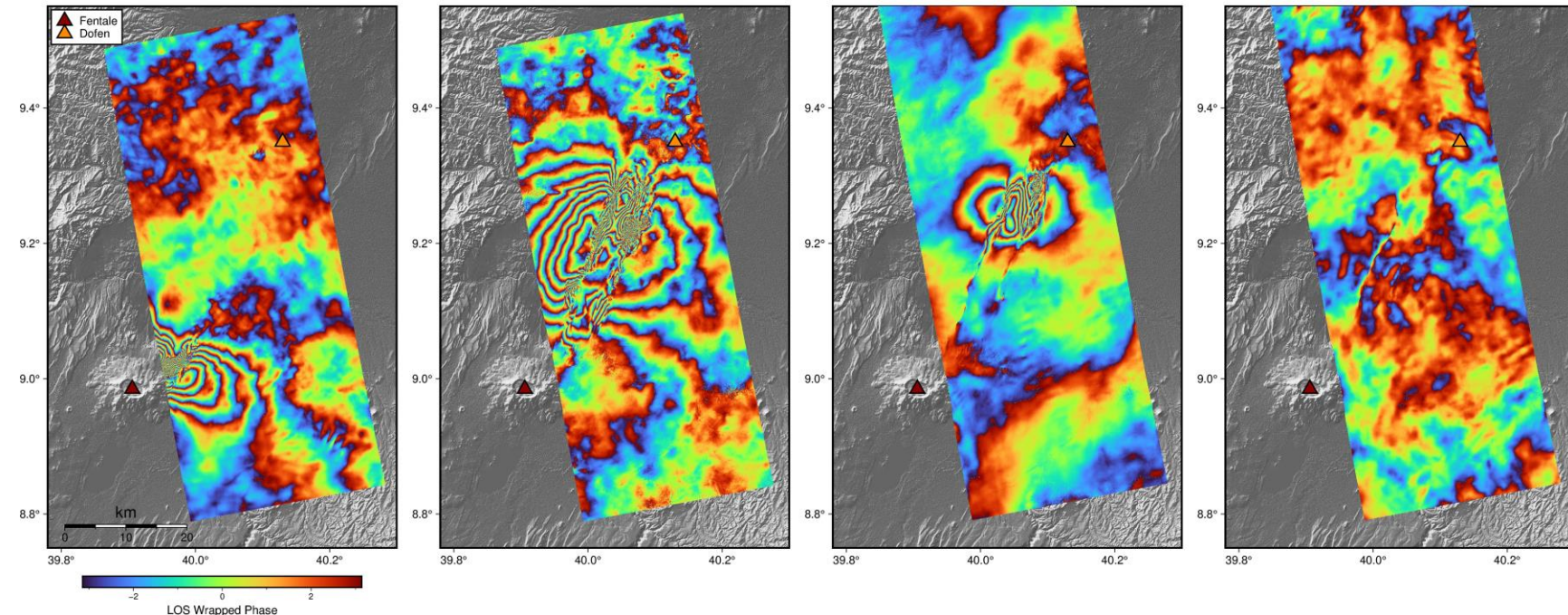
- Unusually high magma compressibility
- Viscoelastic contribution to deformation.
- Secondary source

CSK/CSG

High spatial and
temporal resolution

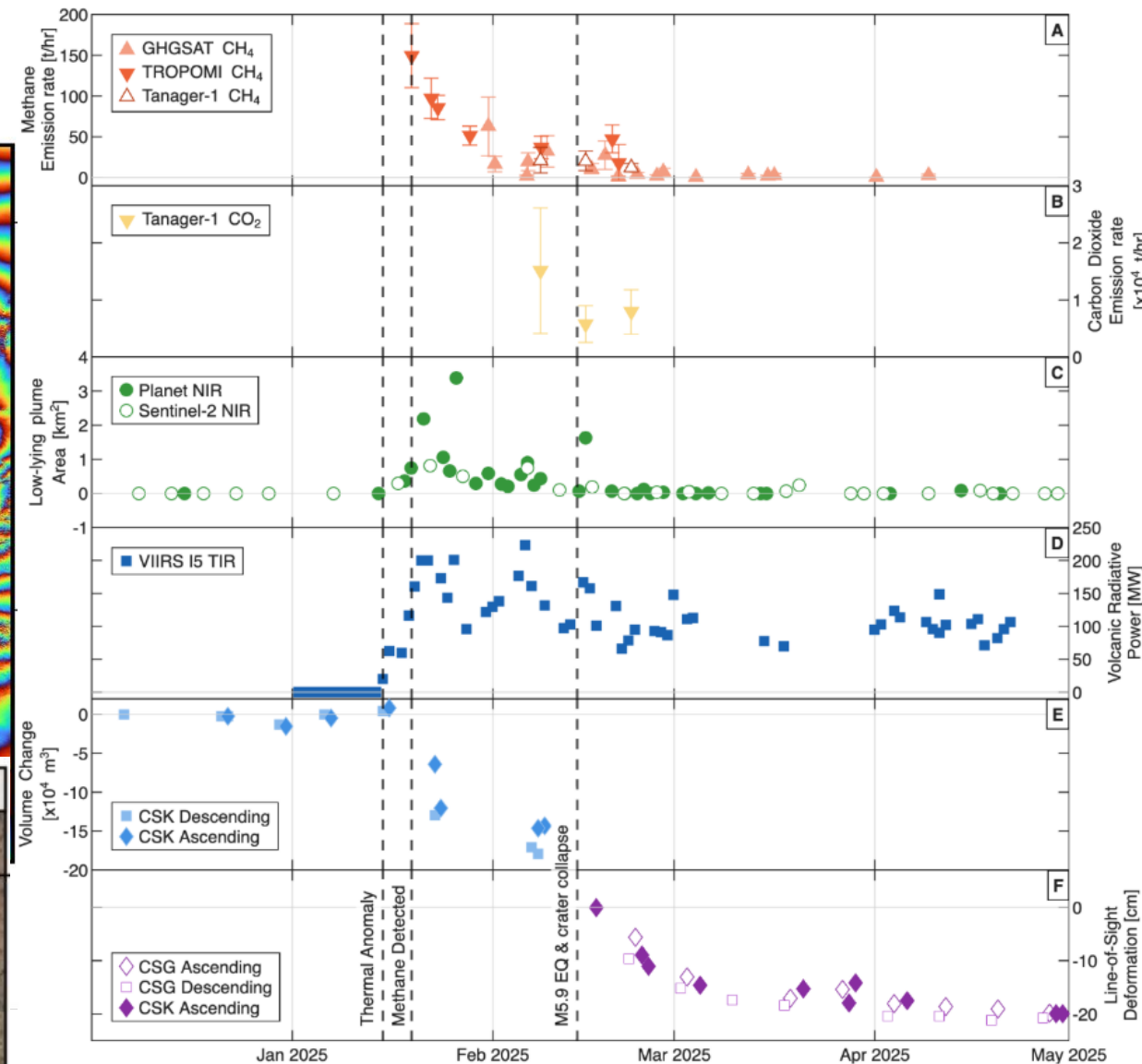
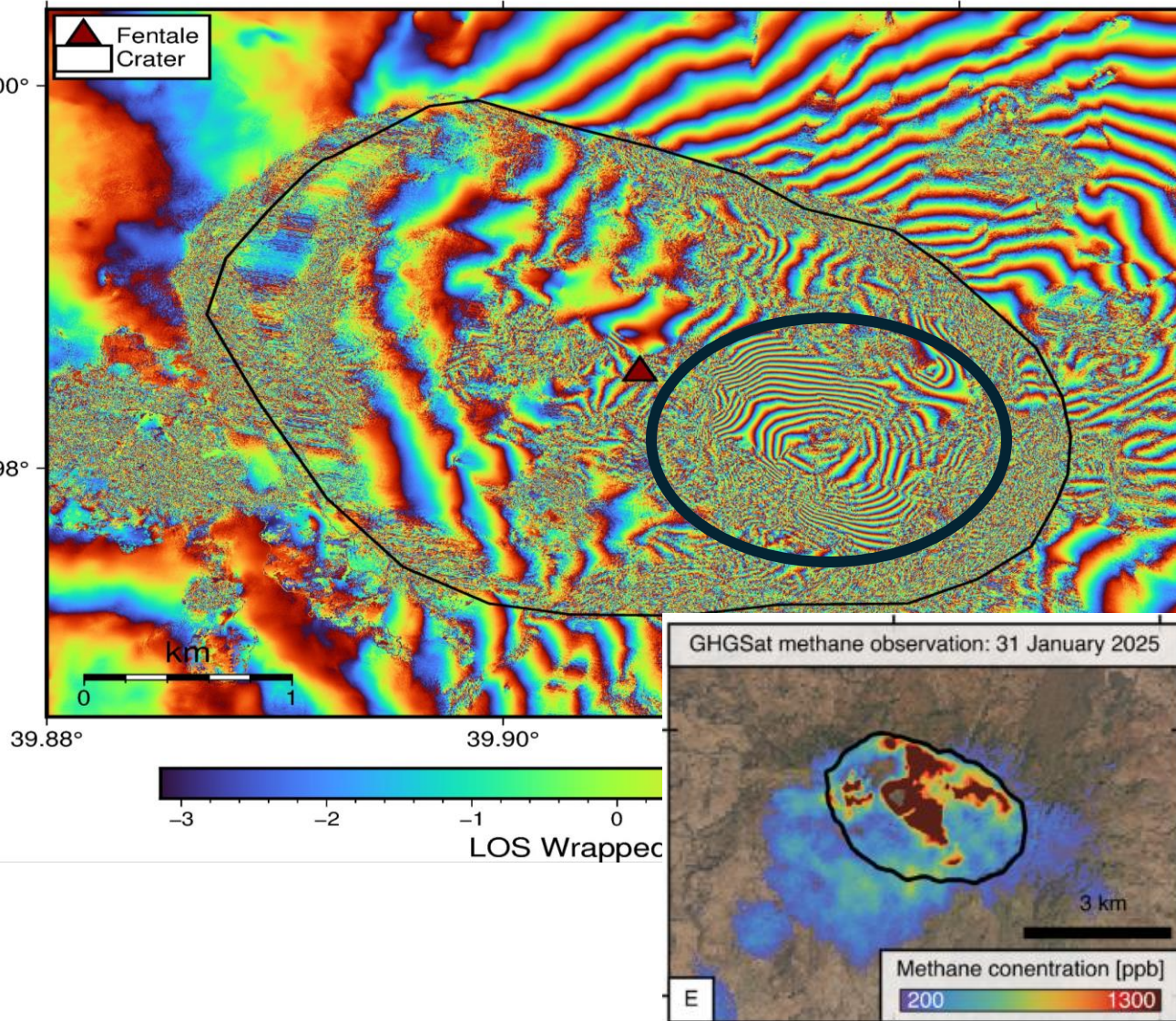


Sequence of 1-day
interferograms



Intra-caldera Deformation.

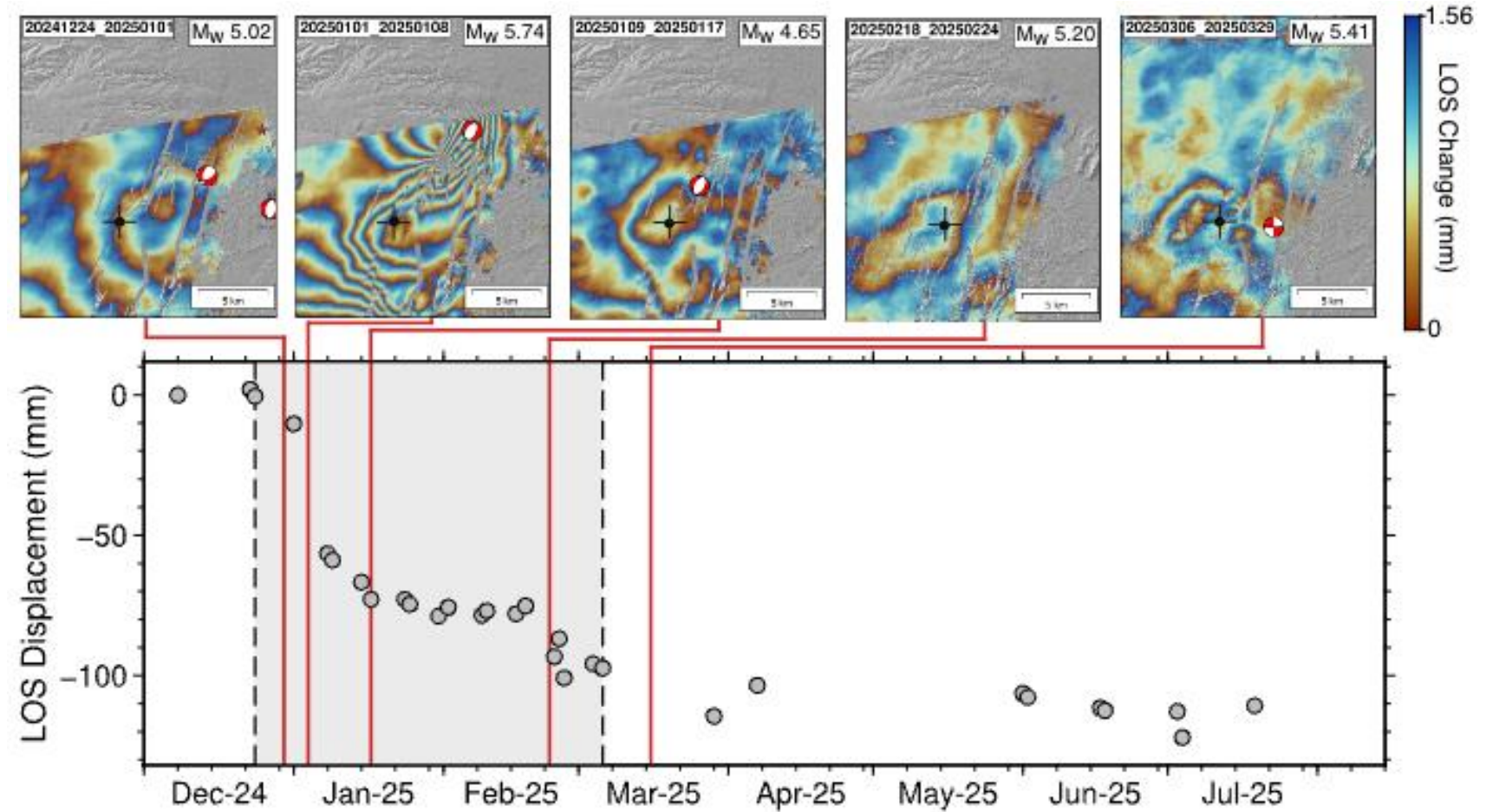
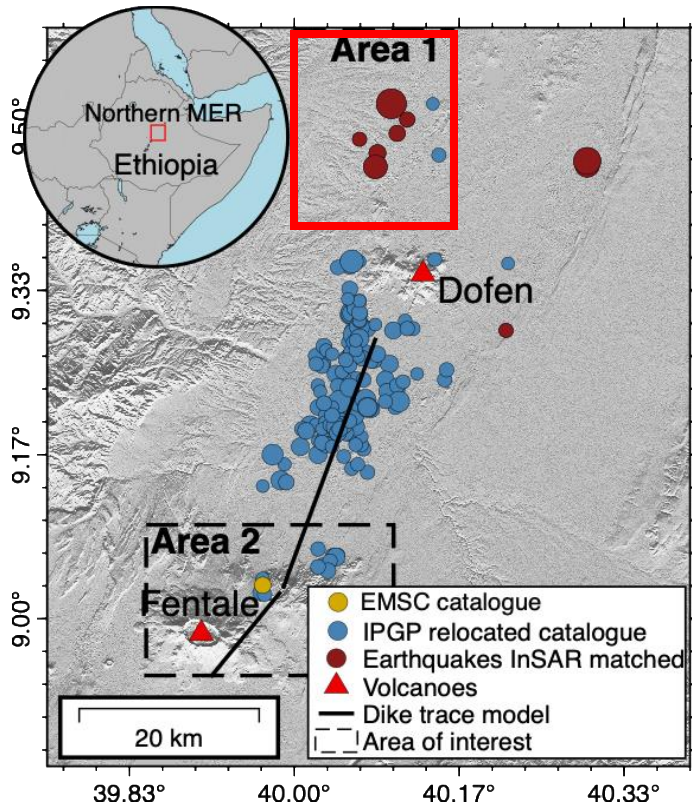
First satellite observation of methane from a volcano.



Dualeh et al, in revision, Nature Geoscience

Faulting in Magmatic Systems

See: Simon Orrego talk,
Earthquakes and Tectonics 1



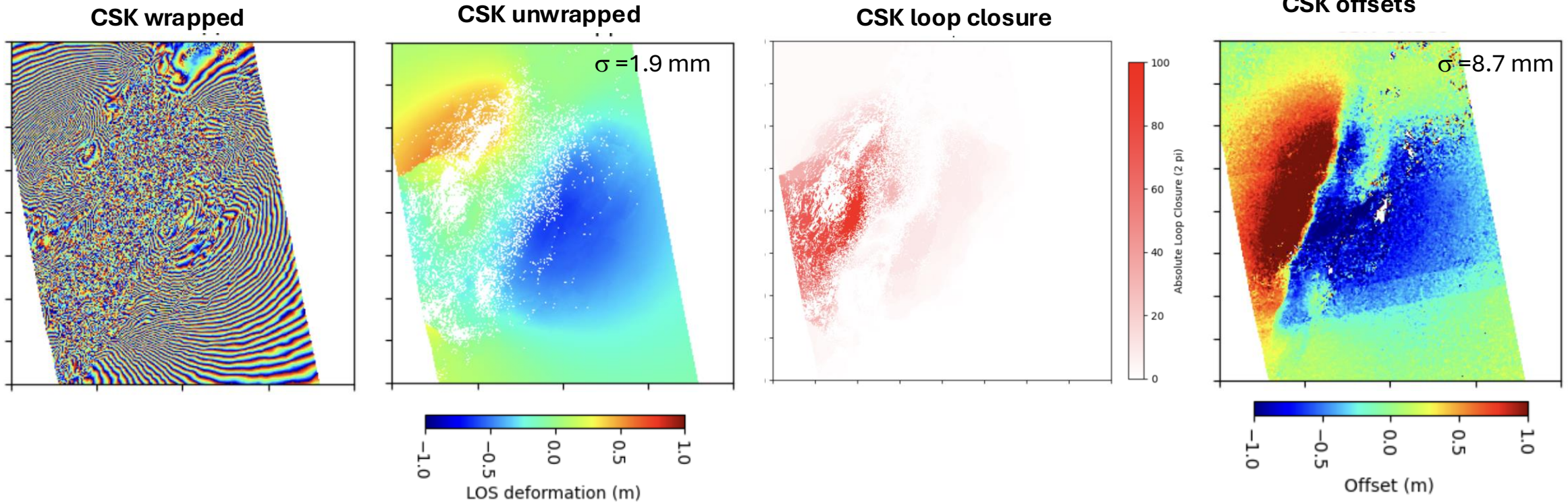
CSK: Challenges of unwrapping

■ Unwrapping Challenges:

- Large displacement gradients with X-band
- Complex deformation patterns involving faults

■ Offset tracking:

- Frame merging issue
- Noisy



CSK: Offset-support unwrapping

■ Concept:

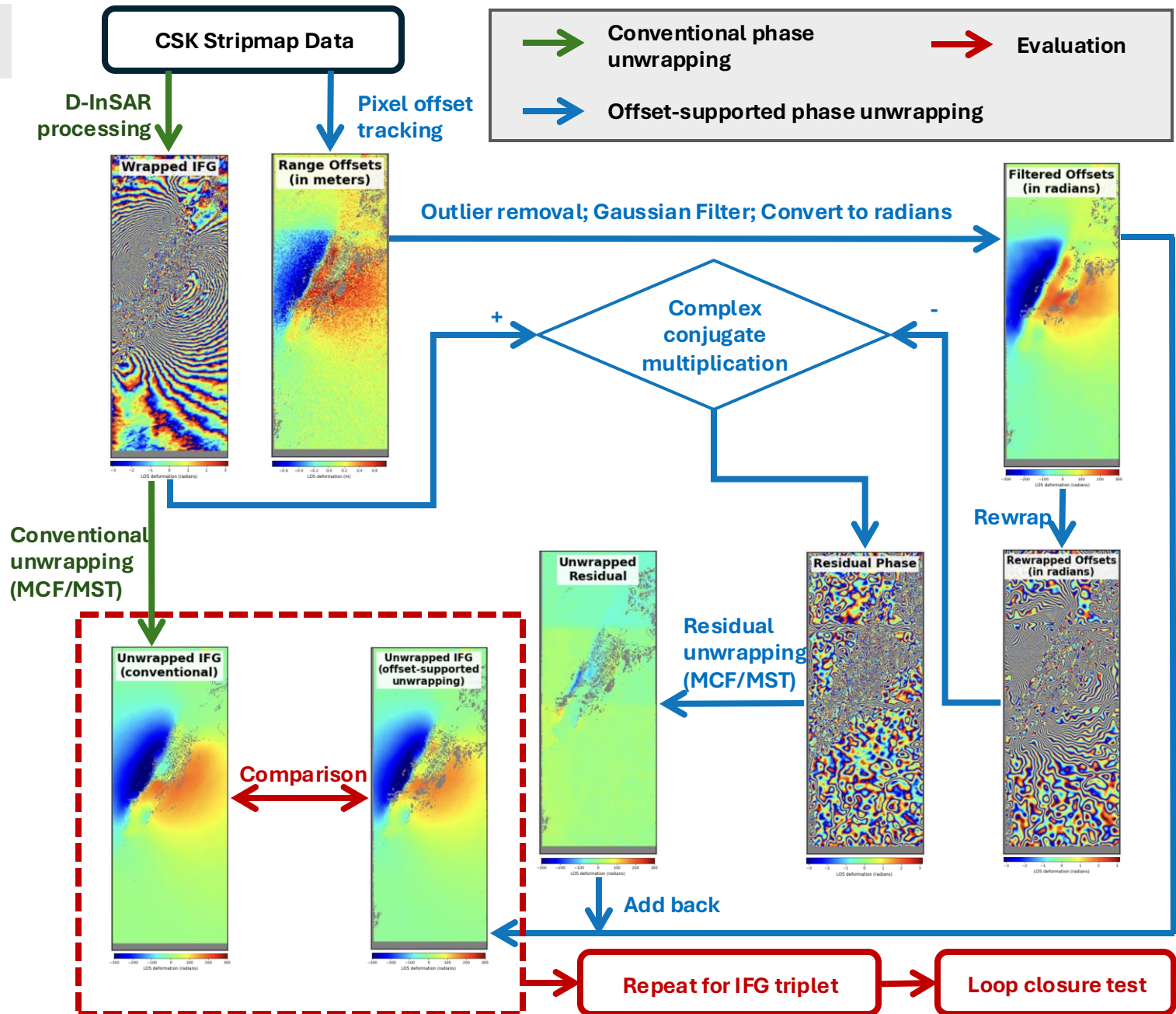
- Use pixel range offsets as the reference deformation field to guide unwrapping

■ Workflow

- Standard D-InSAR processing and multi-kernel offset tracking
- Filter offset map and generate residual interferogram
- Unwrap residual interferogram which reduces jumps
- Add unwrapped residual to filtered offset

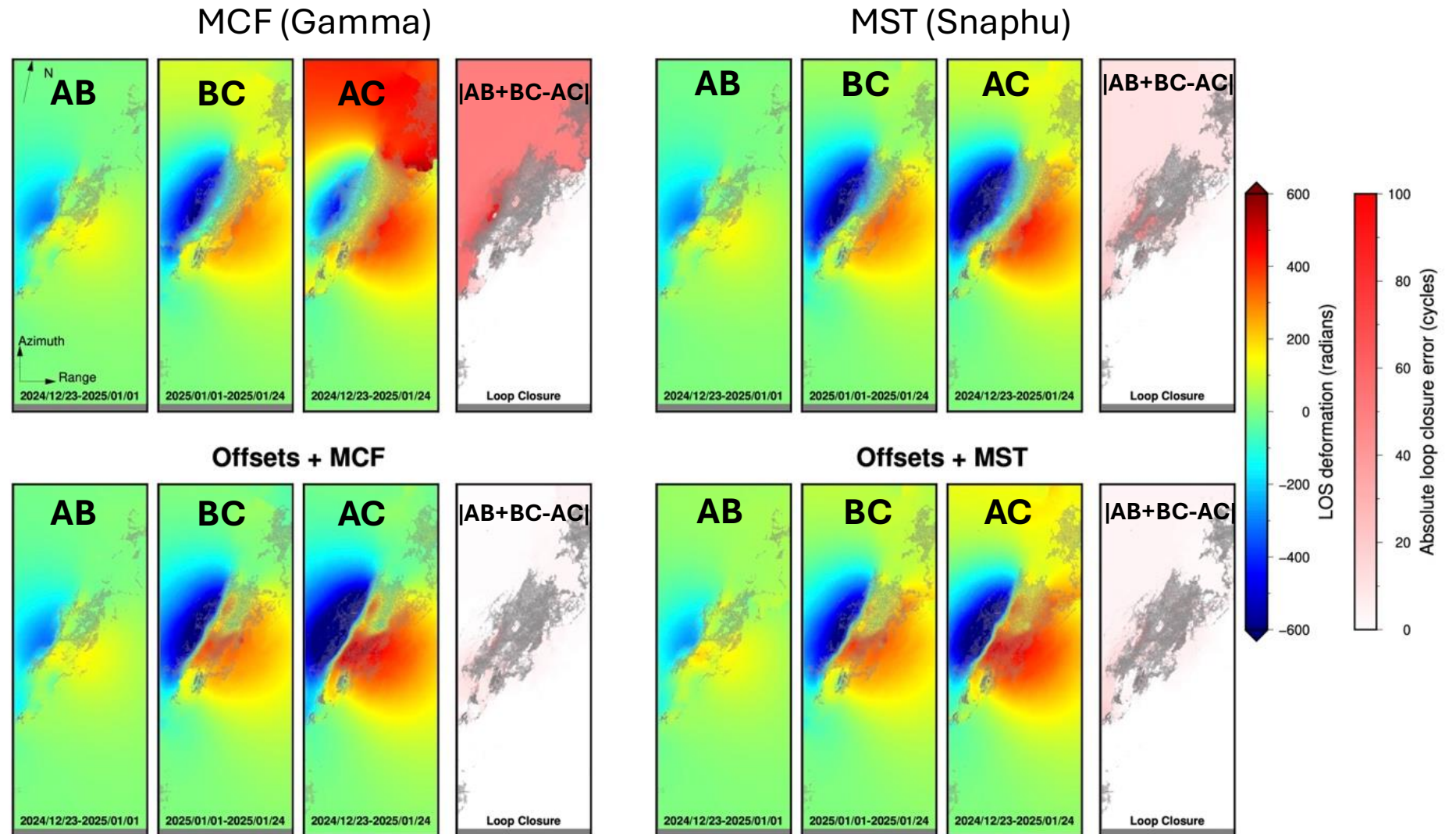
■ Comparison of 4 method

- MCF (GAMMA)
- MST (SNAPHU)
- Offsets+MCF
- Offsets+MST

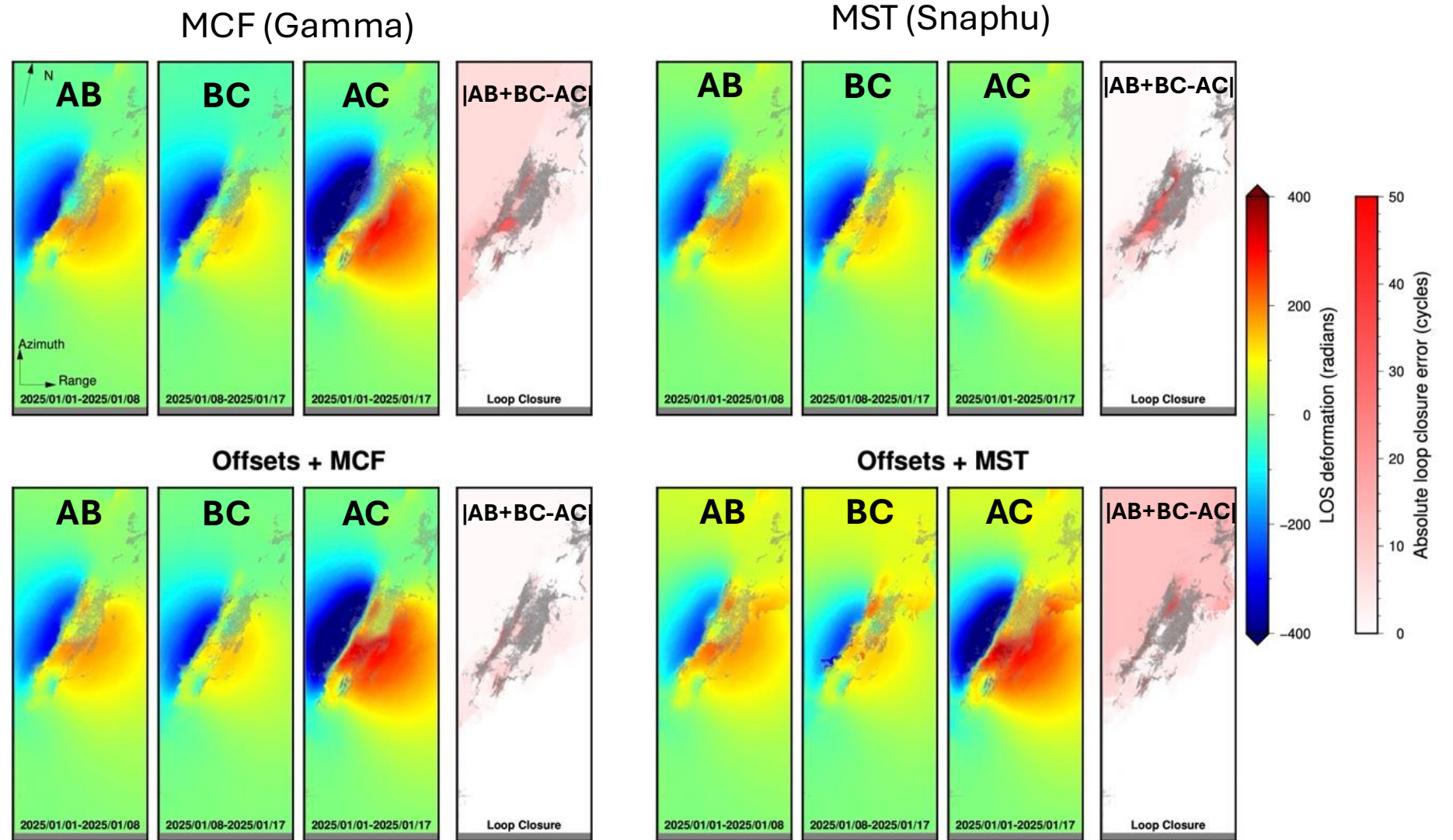


Example 1:

Ascending track CSK H4-22 is chosen for research: contains two dike opening lobes and graben



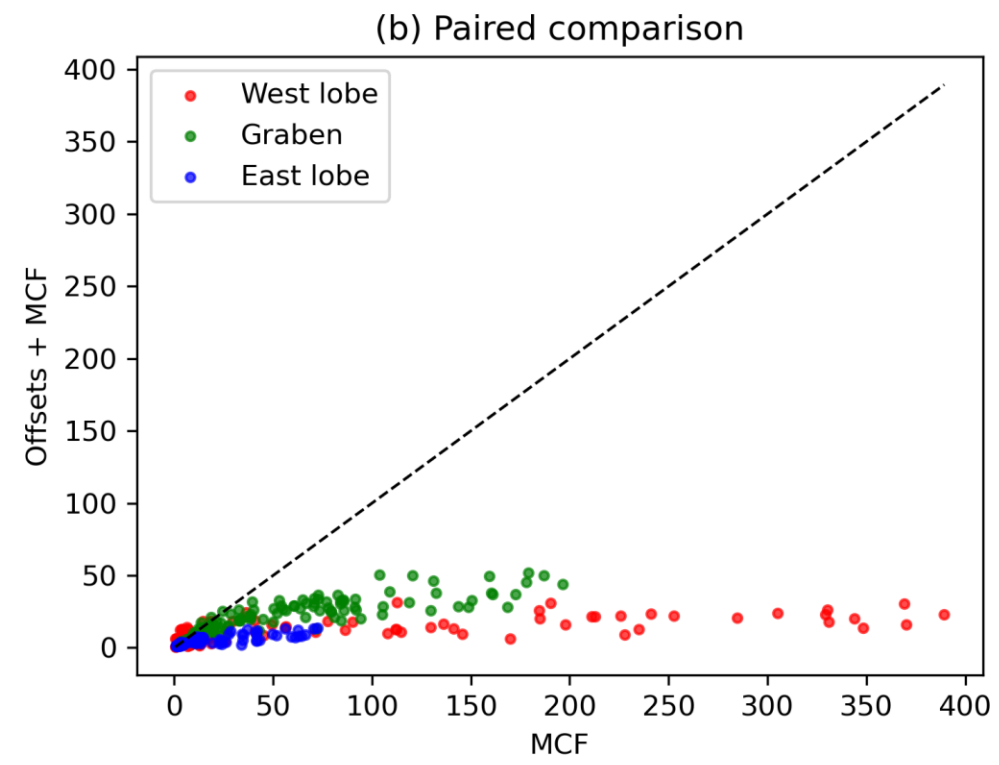
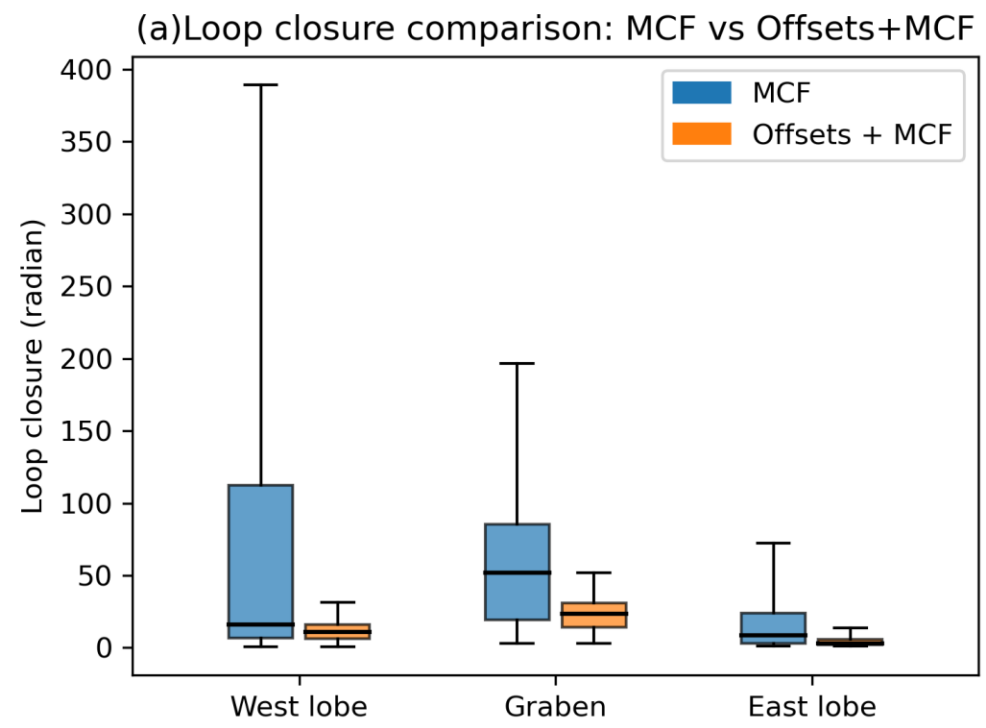
Example 2:



Offsets+MCF consistently produces the smallest loop-closure residuals

Loop closure statistics

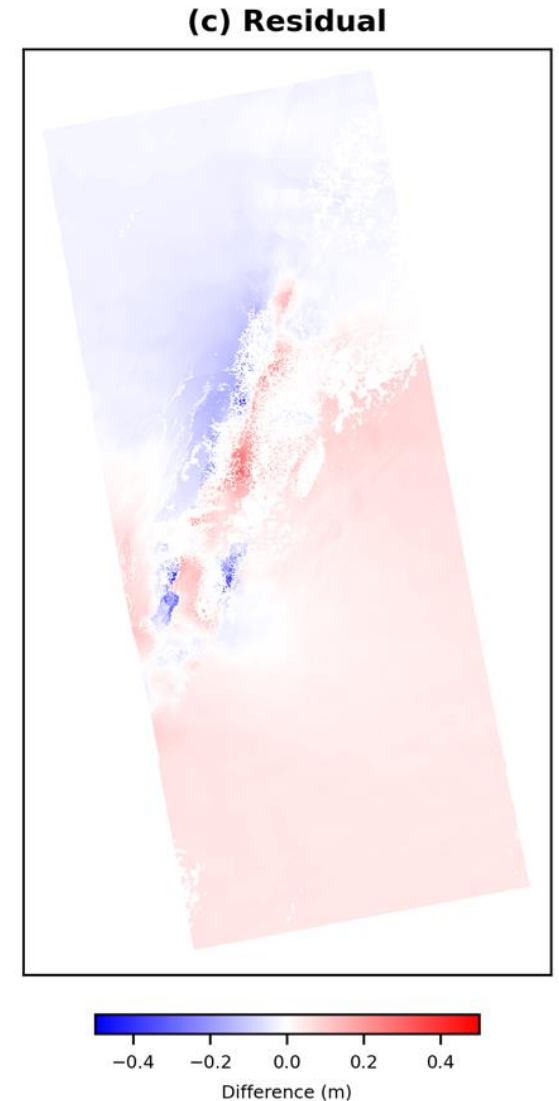
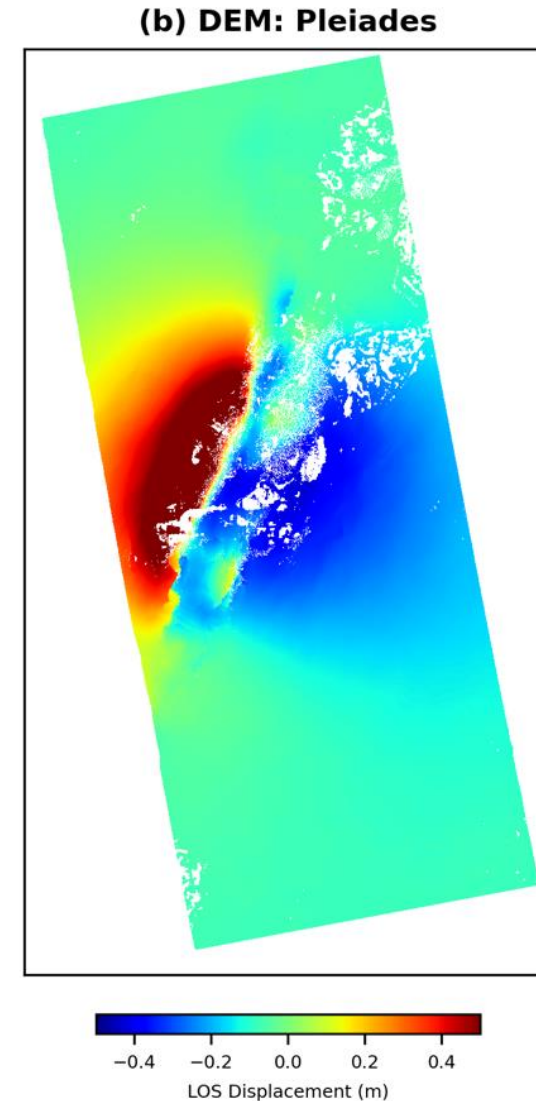
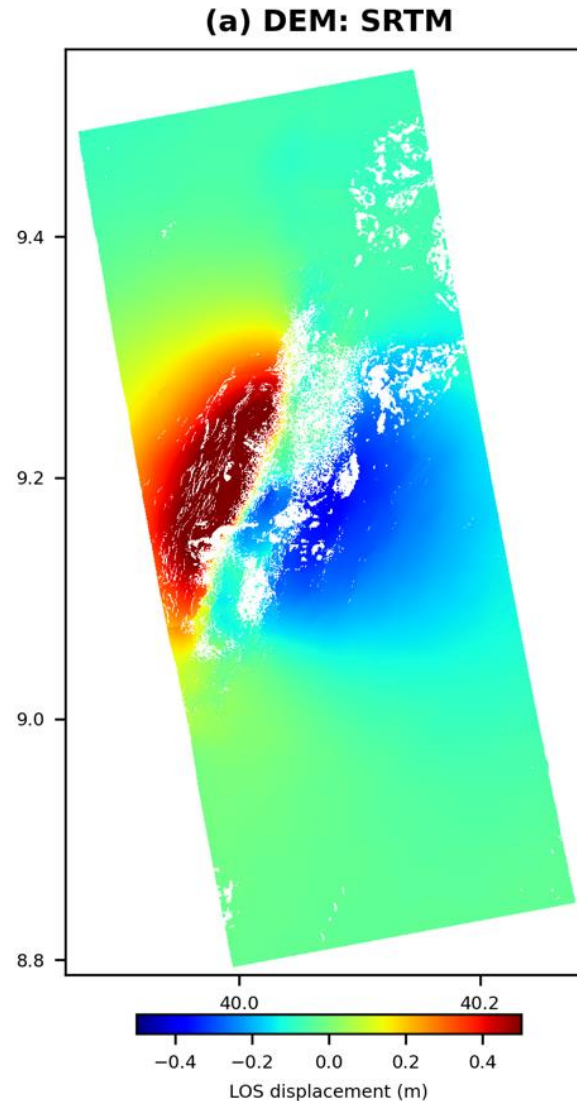
- **Dataset**
 - 61 interferograms
 - 109 triplets



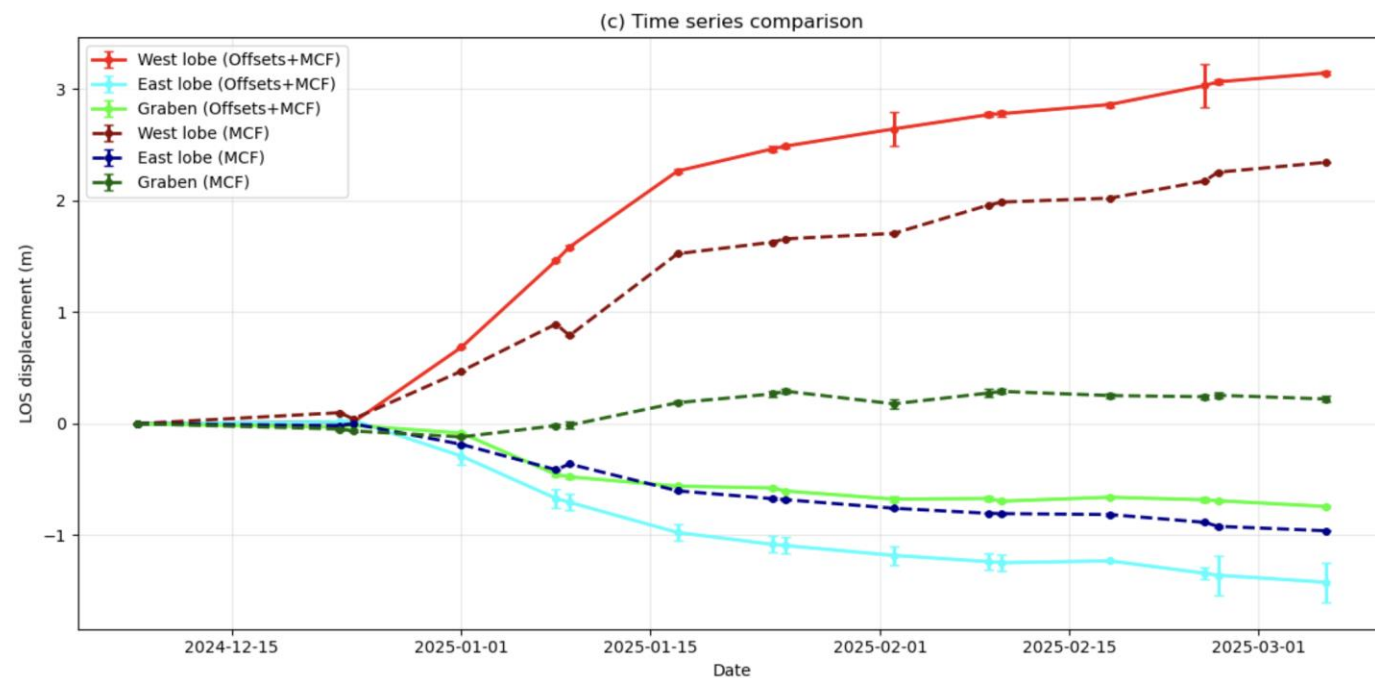
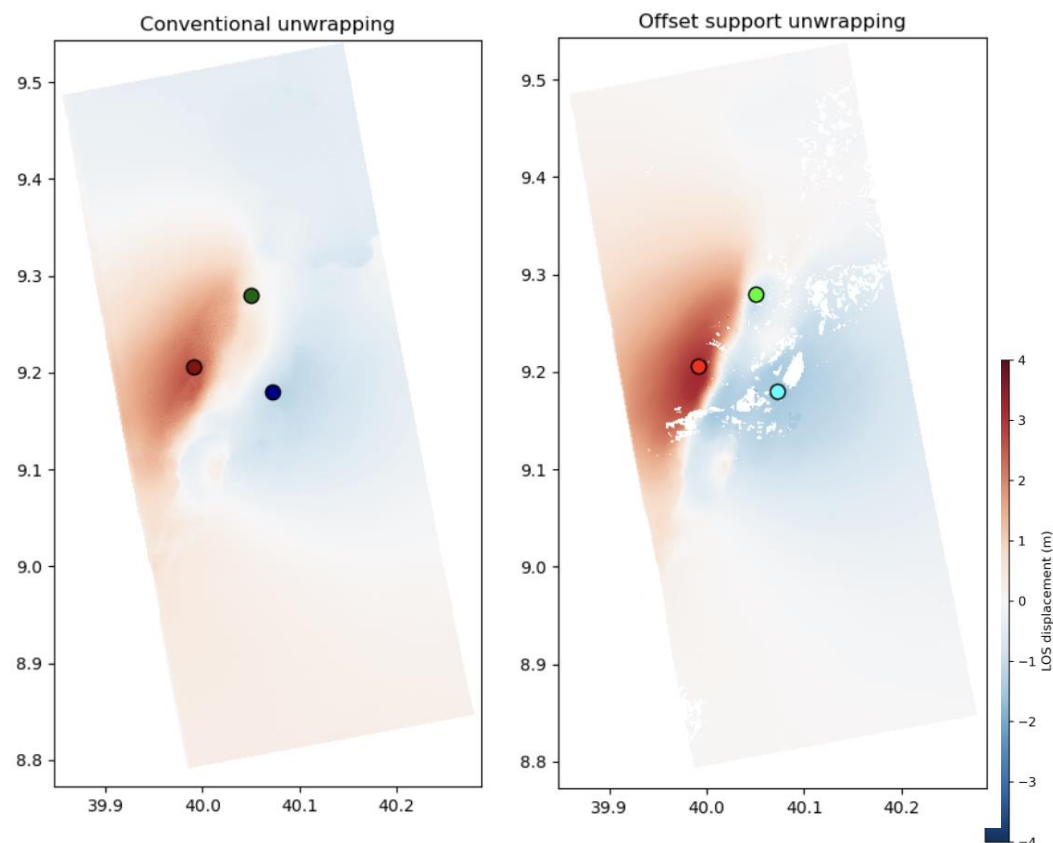
Offsets+MCF reduces the magnitude and dispersion of loop error

Importance of High-Resolution DEMs

- **Original interferogram:**
 - 8-m resolution
- **DEM used in (a):**
 - 30m SRTM resample to 8 m
- **DEM used in (b):**
 - 1m Pleiades resample to 8 m
- **High resolution DEM helps capture more details inside graben area**



Time-series results (LiCSBAS)



- **LOS total displacement**
- West lobe: 3.14 ± 0.02 m
- Graben: -0.74 ± 0.01 m
- East lobe: -1.42 ± 0.17 m

Comparison: Total LOS displacement (ascending track)

CSK

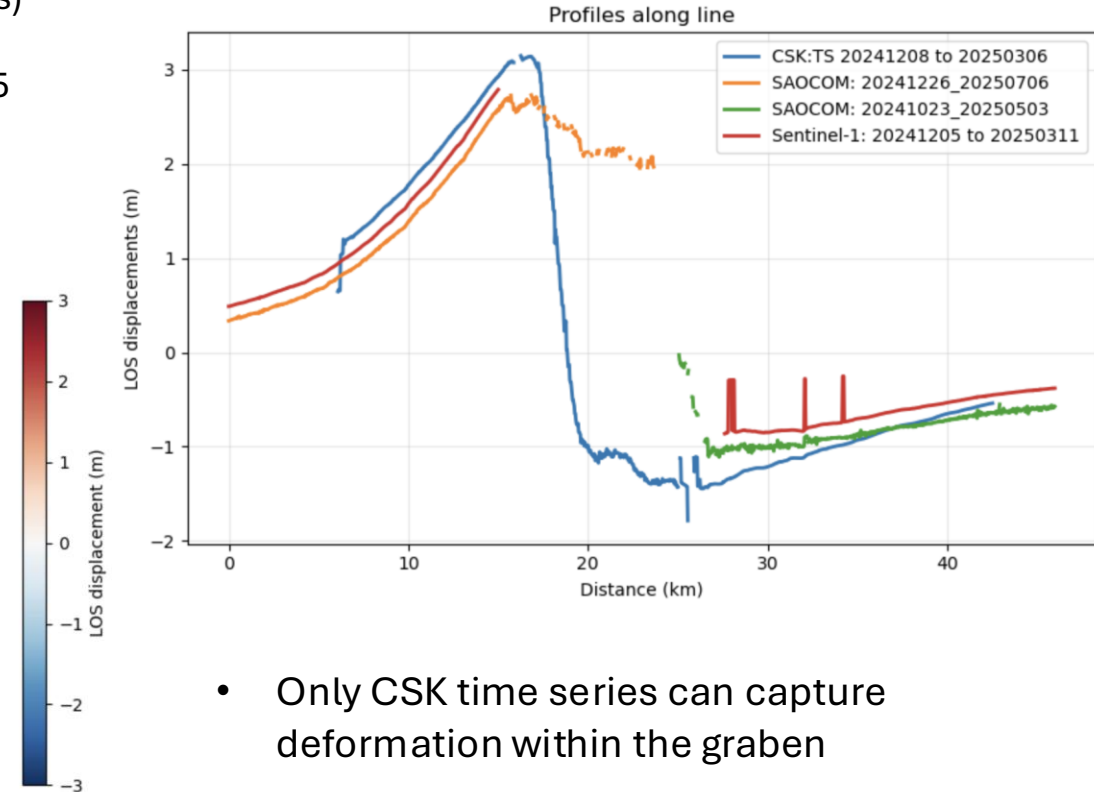
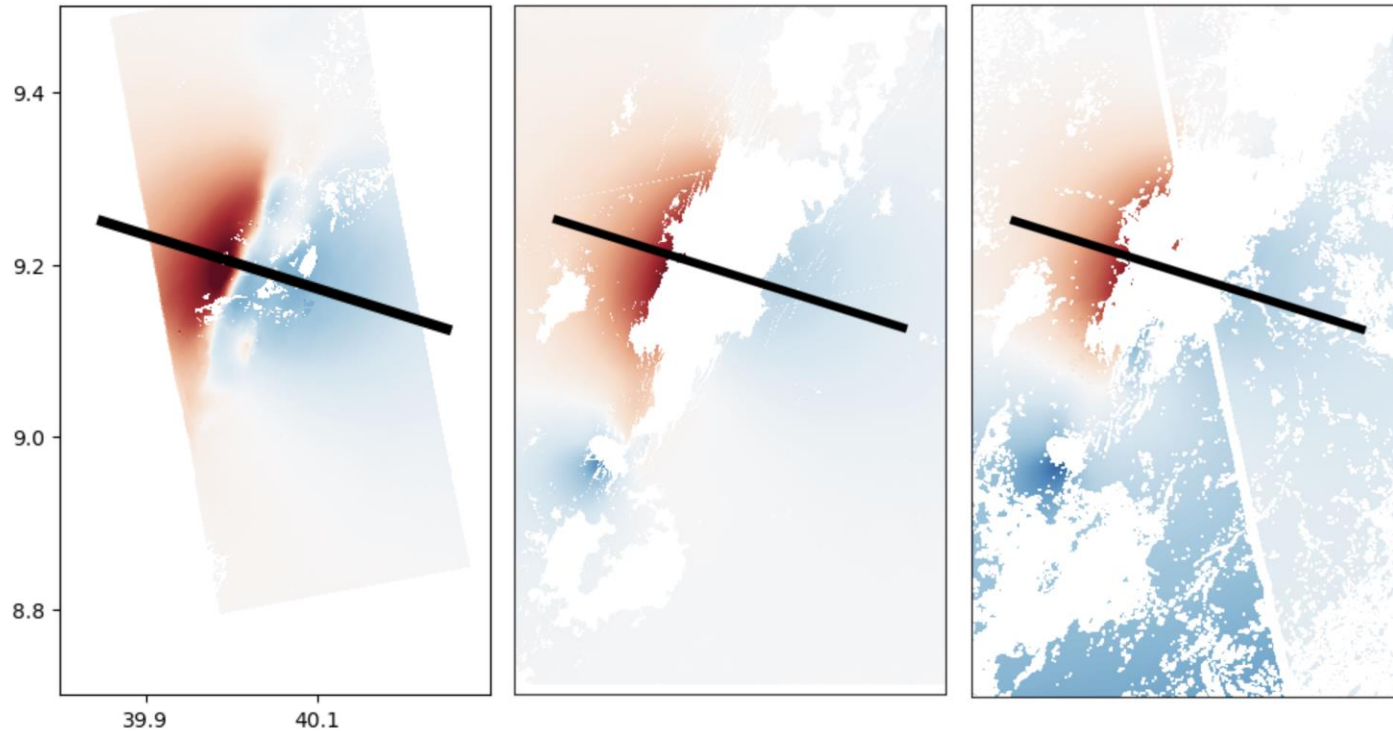
- Time series
- Dec 2024 - Mar 2025
- **Incidence: 57°**

Sentinel-1

- Sum of 7 consecutive interferograms
- Dec 2024 - Mar 2025
- **Incidence: 40°**

SAOCOM

- 1 interferogram (4 frames)
- Dec 2024 - July 2025
- October 2024 - May 2025
- **Incidence: 43°**



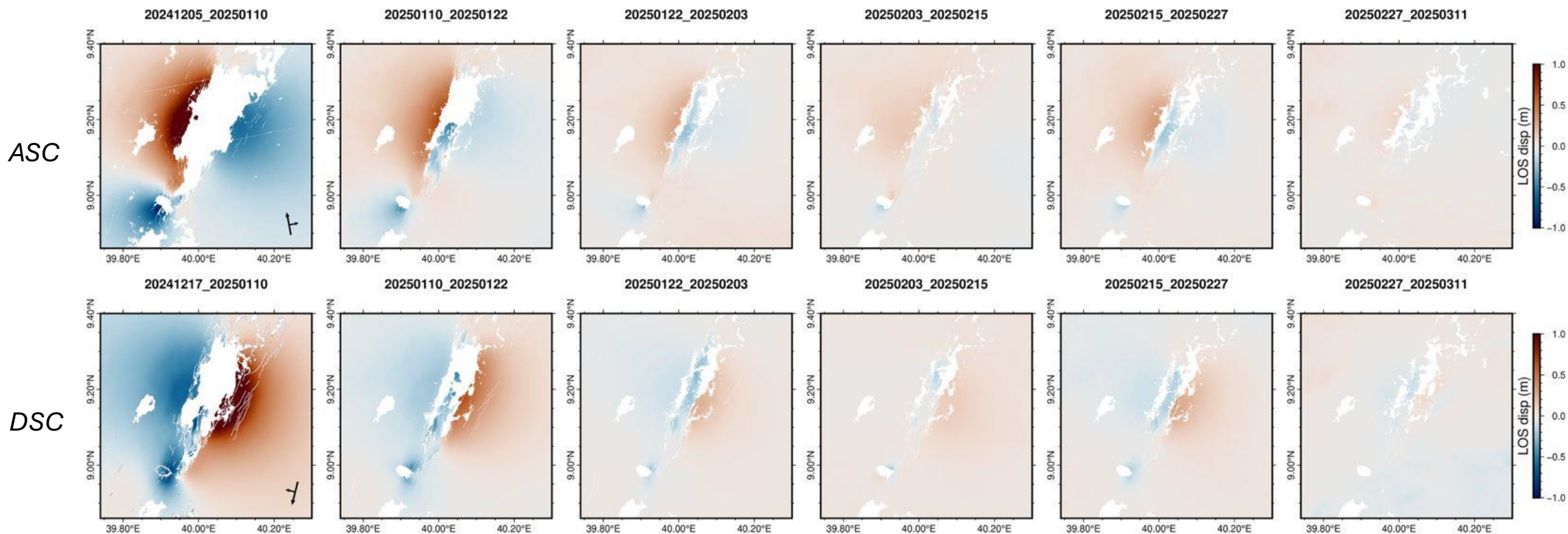
- Only CSK time series can capture deformation within the graben
- East lobe profile trend: Sentinel-1 and SAOCOM are similar, might be related with similar incidence angle

Take-aways

- **2024-2025 Fentale-Dofen dike intrusion, Ethiopia**
 - Dike intrusion: **~50 km** long, **~10,500 km²** affected, LOS displacement up to **~3 m** in **~60 days**
 - The complex widespread and rapidly evolving deformation require **synergistic use of multi-mission InSAR**
- **C-band Sentinel-1**
 - **Regular, regional coverage**
 - **Real-time response**
 - **Large-scale modelling**
- **X-band CSK**
 - High-spatial resolution: **~3 m**
 - Dense temporal sampling: **1,8,16 days** during the event
 - **Offset support unwrapping** can help with **time series** processing
- **L-band SAOCOM**
 - Revisit time: months
 - **Independent constraint** on large deformation

Sentinel-1: Manually Tuned Unwrapping

- Not feasible for routine processing of large amount of interferogram
- Applied only to 7 consecutive 12-day interferograms



SAOCOM

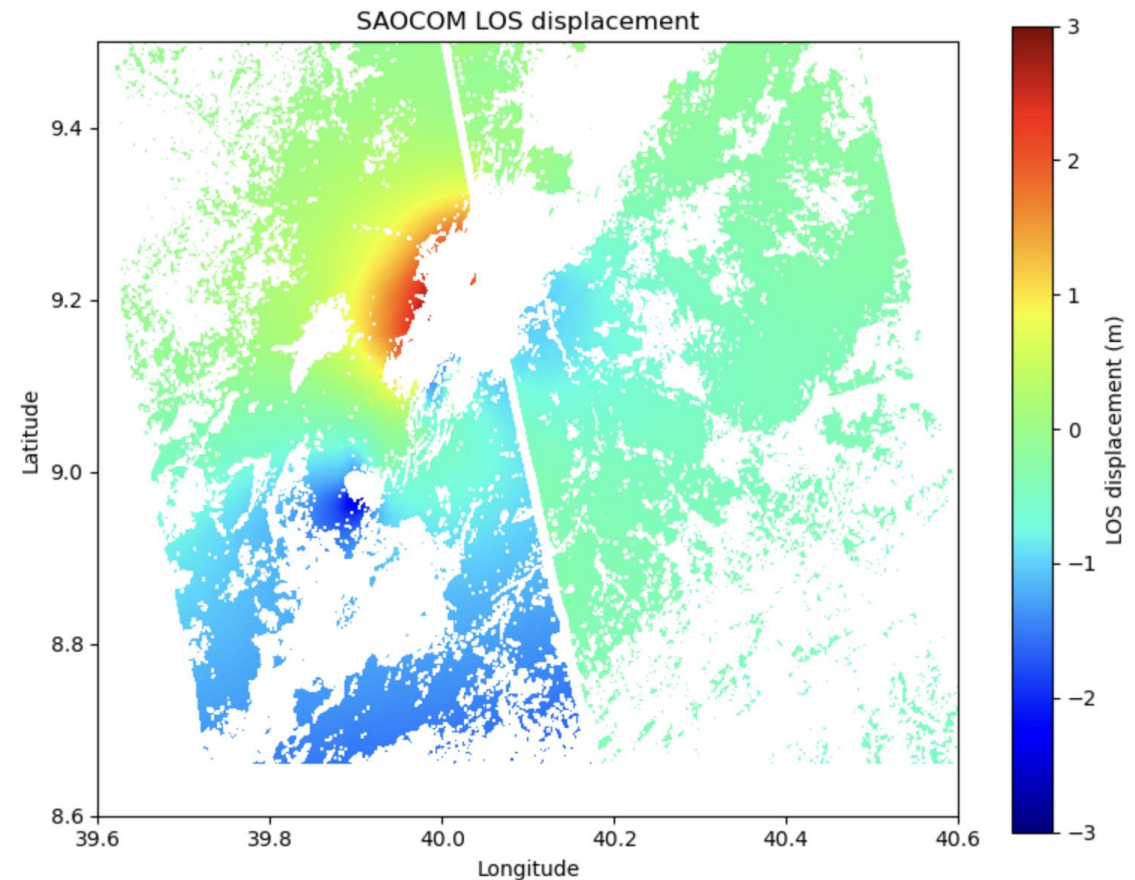
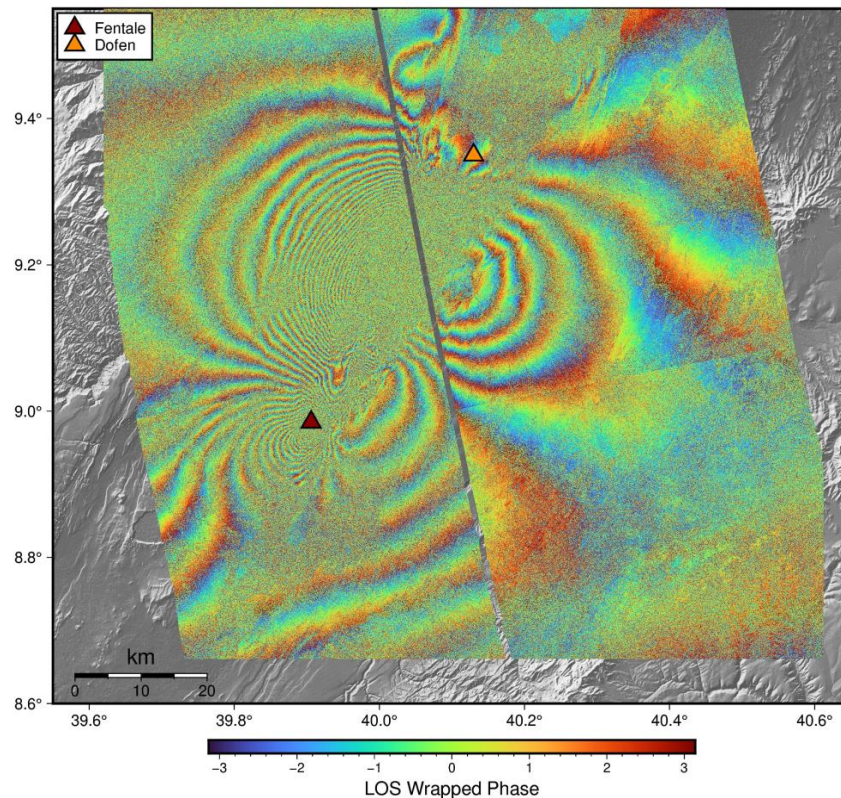
- Merge 4 frames for the whole region
- Revisit time: months
- 1 interferogram cover whole event

- Bad coherence due to long temporal baseline
- Easier unwrapping: MCF unwrapping (default setting) is acceptable

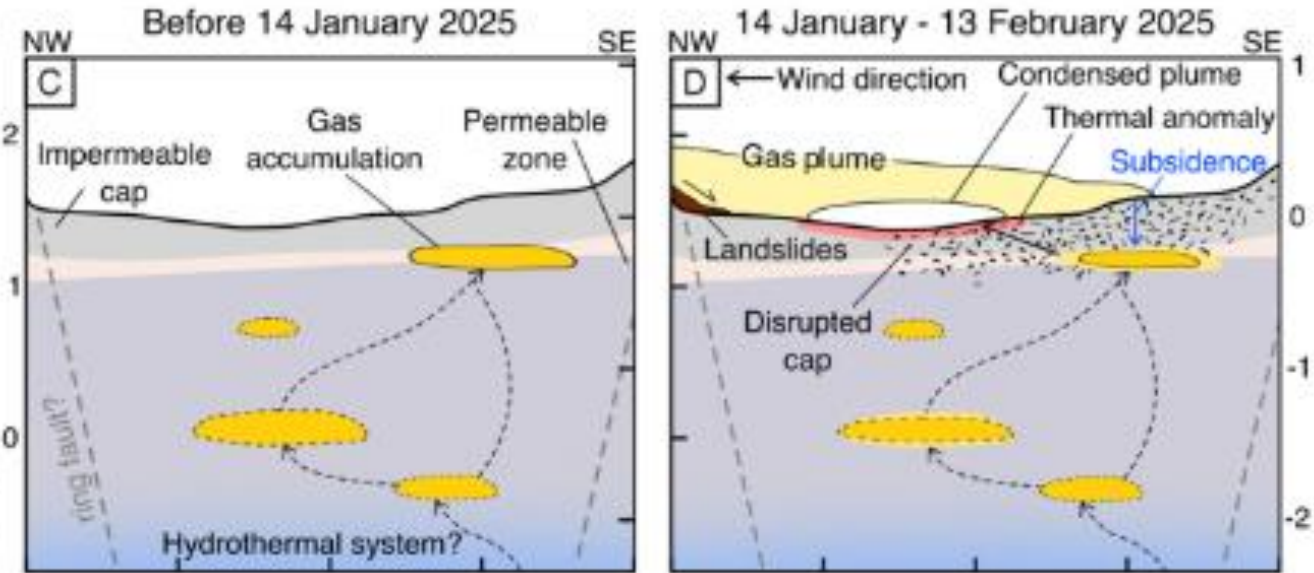
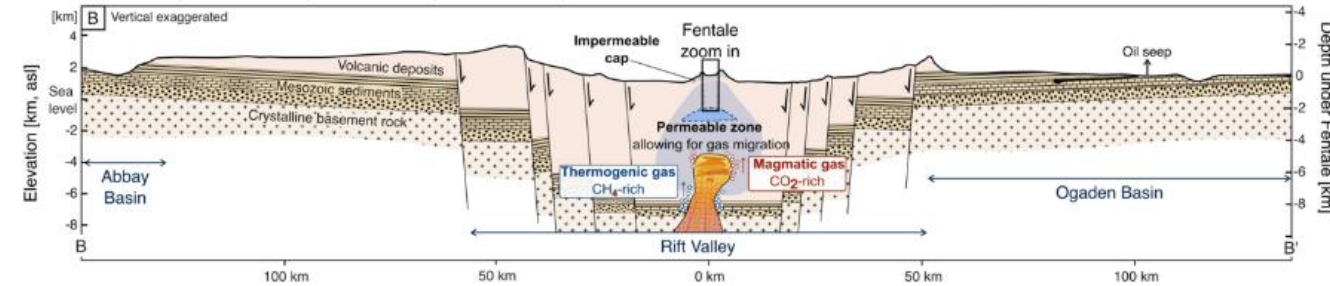
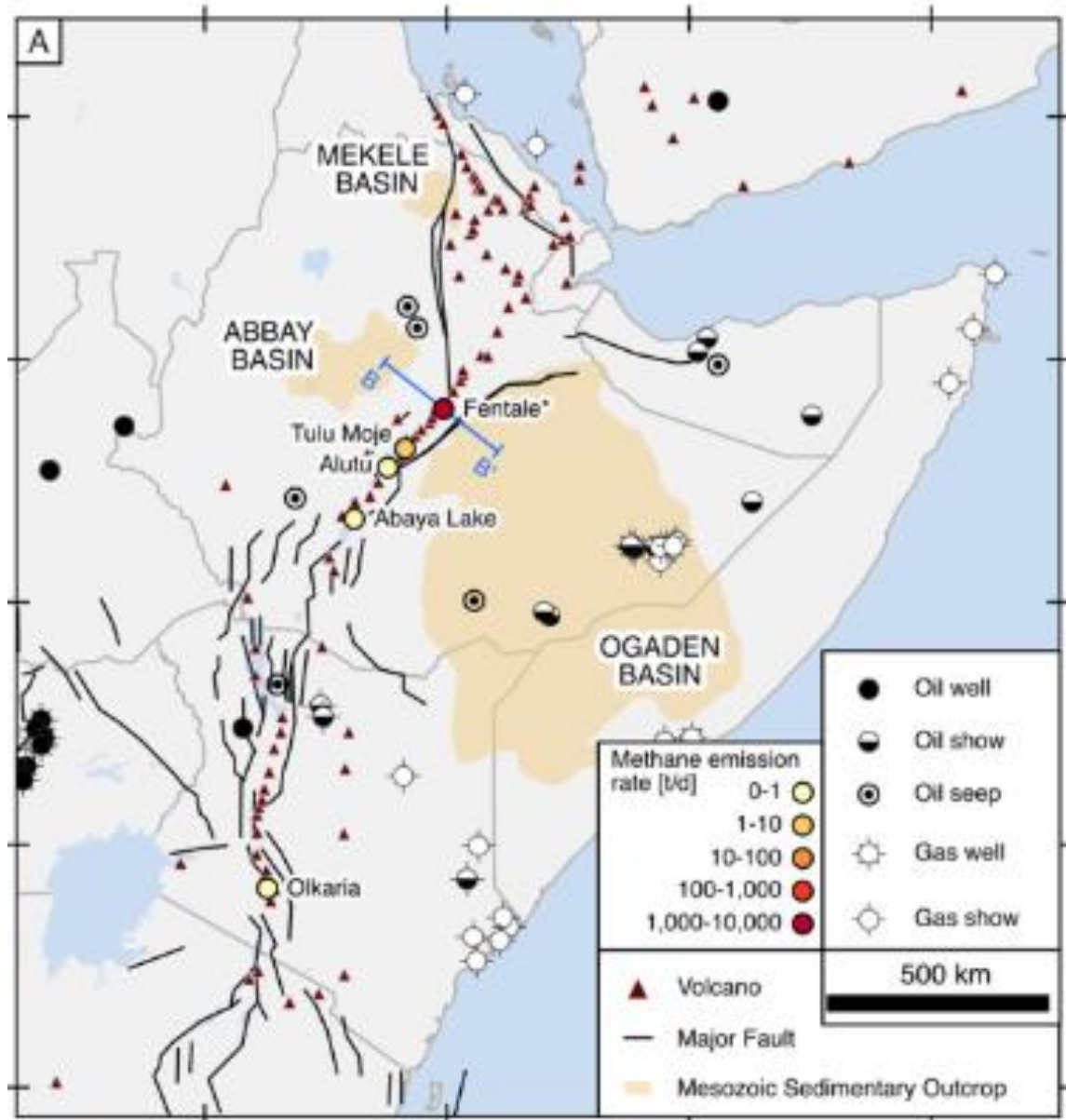
SAOCOM total deformation

Left: 2024/09/21-2025/07/06

Right: 2024/10/23-2025/05/03



Where did the methane come from?

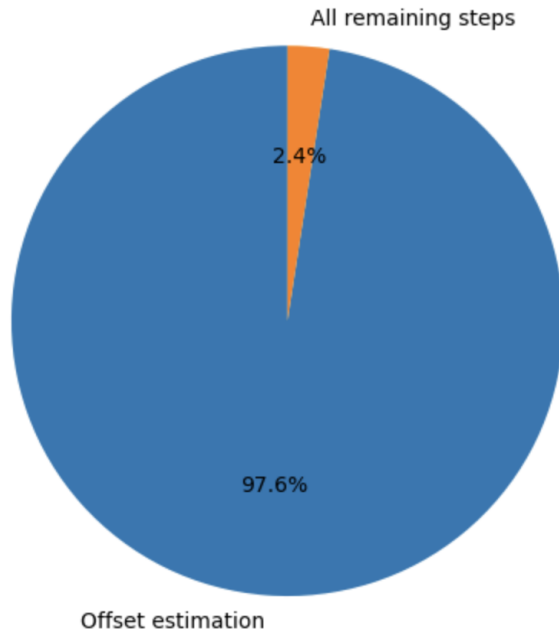


Similar mechanism to the one proposed for the link between LIPS and hyperthermals.

CSK offset support unwrapping: Computational Cost

- **AMD EPYC 7402P processor**
 - 24 physical cores,
 - 48 threads
 - 251 GB RAM

Computational Cost of Offsets+MCF Workflow



Method	Offset Estimation	Steps to get residual IFG	Unwrapping	Total
MCF	0	0	5–10 min	5–10 min
Offsets+MCF	8–12 h	8 min	~5–10 min	8–12 h
MST	0	0	2 h–2 d	2 h–2 d
Offsets+MST	8–12 h	8 min	2 h–2 d	10 h–60 h