



Supplement of

Long-term InSAR and streamflow recession analysis reveal accelerated permafrost degradation in the mining area of the Qilian Mountains

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Table S1 The information of interferograms obtained from ERS-2, Envisat, ALOS-1, and ALOS-2

Satellite	Image 1 (yyyymmdd)	Image 2 (yyyymmdd)	Perpendicular baseline (m)	Time span (days)
ERS-2	19970428	19970602	98	35
	19970811	19980727	-239	350
Envisat	20031018	20051022	-435	735
ALOS-1	20070712	20071012	702	92
	20070712	20080714	-1053	368
	20070827	20090901	-853	736
	20070827	20100904	1225	1104
	20100720	20101020	481	92
ALOS-2	20190324	20200322	307	364
	20190519	20190714	-25	56
	20190714	20200322	386	252
	20200322	20210321	46	364
	20210321	20220320	-273	364

Table S2 Basin-scale statistics of the scaling factor from 2016 to 2022

Period	Mean	STD	CV	Min	Max
Apr28–Jun02	2.50	0.19	0.08	2.31	2.79
Jul12–Oct12	1.82	0.20	0.11	1.57	2.05
Jul20–Oct20	2.04	0.23	0.11	1.70	2.39
May19–Jul14	1.61	0.16	0.10	1.34	1.78

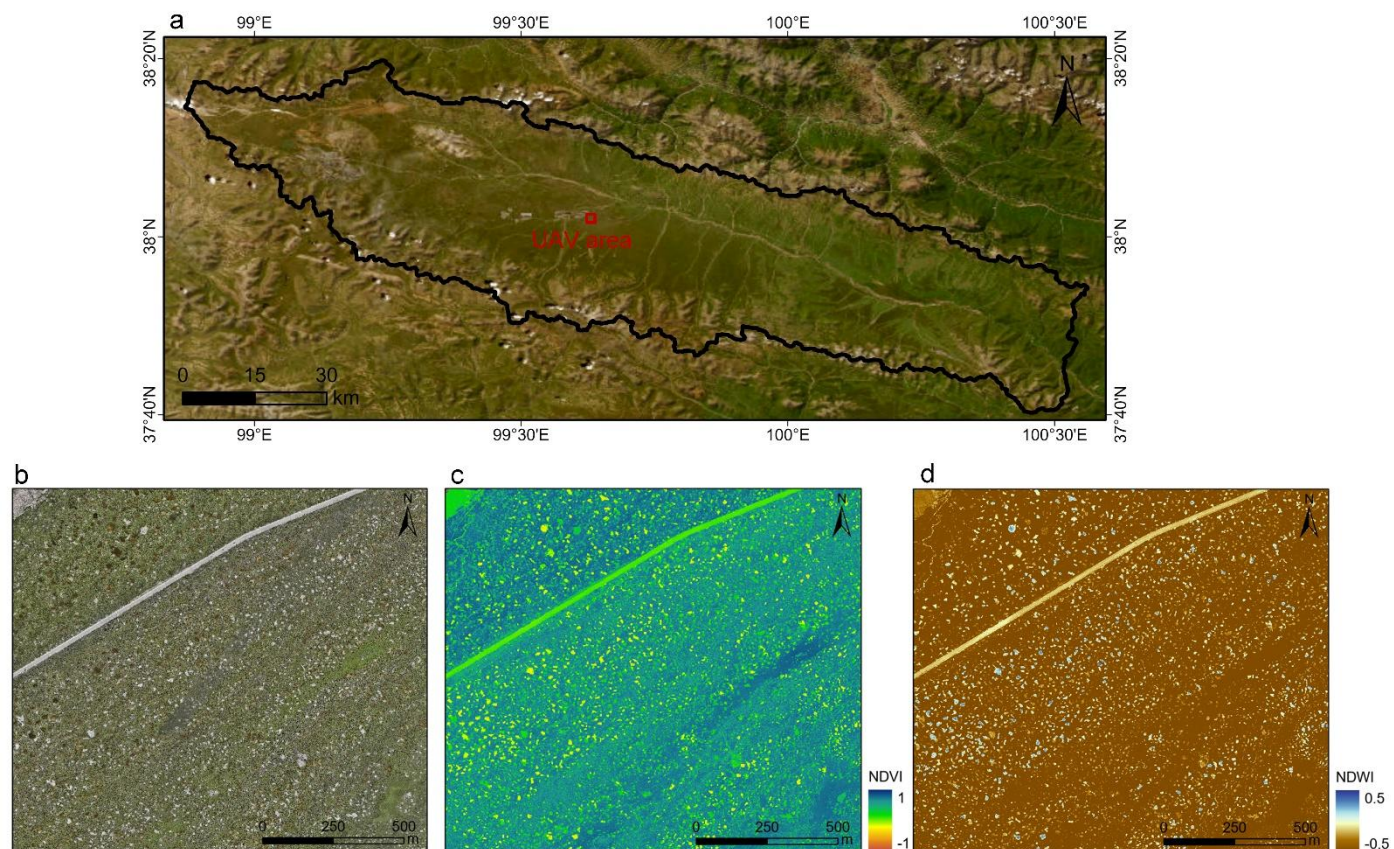


Figure S1 Multispectral unmanned aerial vehicle (UAV) survey of surface conditions around the mining area: (a) survey location, (b) orthophoto, (c) normalized difference vegetation index (NDVI), and (d) normalized difference water index (NDWI). The optical basemap in panel (a) is from Esri | Powered by Esri.

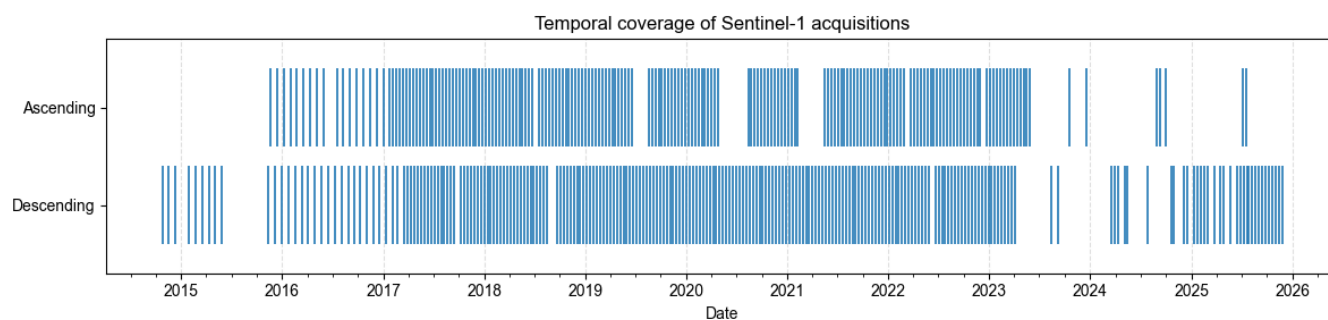


Figure S2 Temporal distribution of ascending and descending Sentinel-1 acquisitions of the study area.

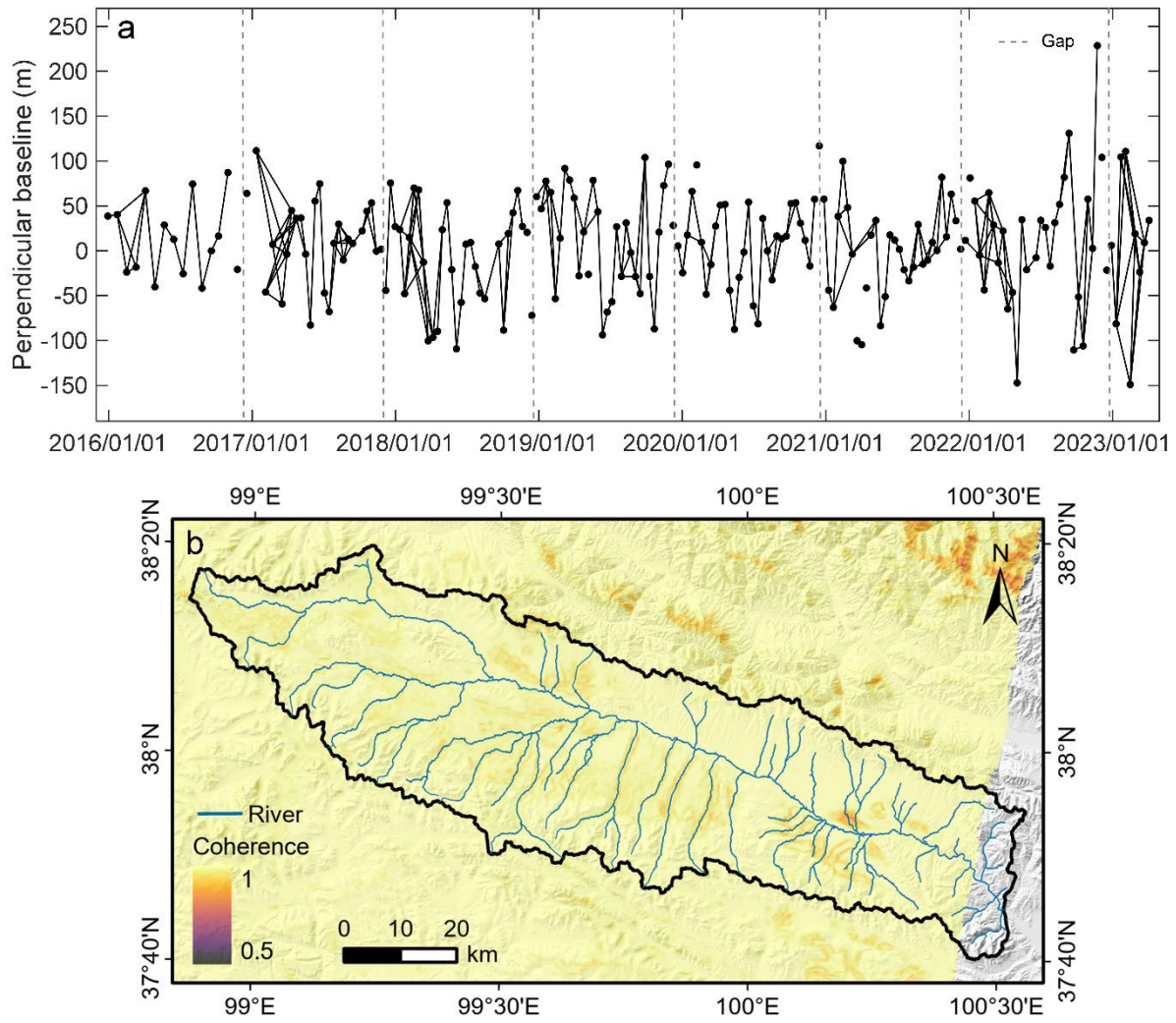


Figure S3 Sentinel-1 interferogram network (a) and average spatial coherence (b).

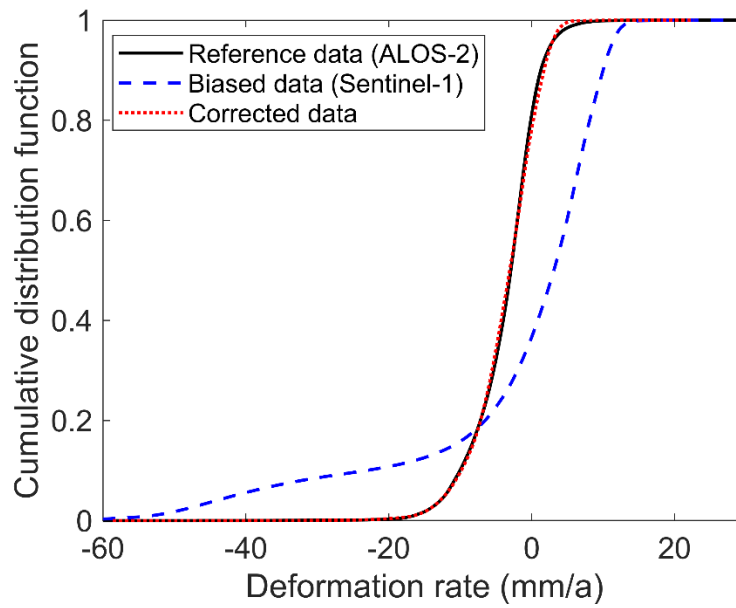


Figure S4 Cumulative distribution function (CDF) matching between Sentinel-1 and ALOS-2 deformation rates. The initial Sentinel-1 deformation rates were corrected to align with the reference ALOS-2 data.

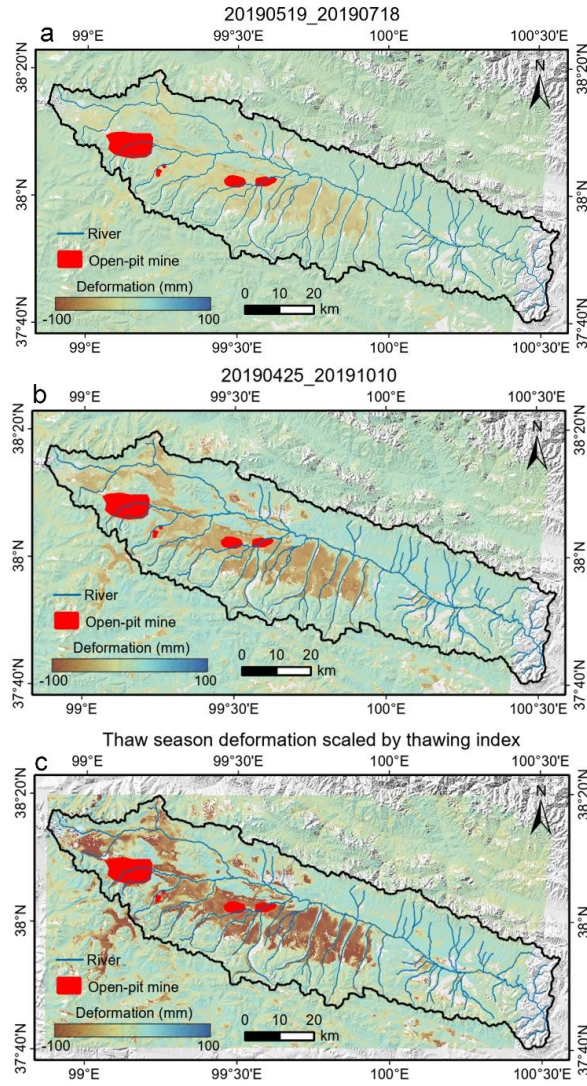


Figure S5 Comparison between actual observed thaw-season deformation and thaw-season deformation scaled using the thawing index. (a) Partial-season deformation from May–July 2019 derived from the Sentinel-1 interferogram network. (b) Actual observed thaw-season deformation in 2019 from Sentinel-1. (c) Thaw-season deformation scaled using the thawing index.

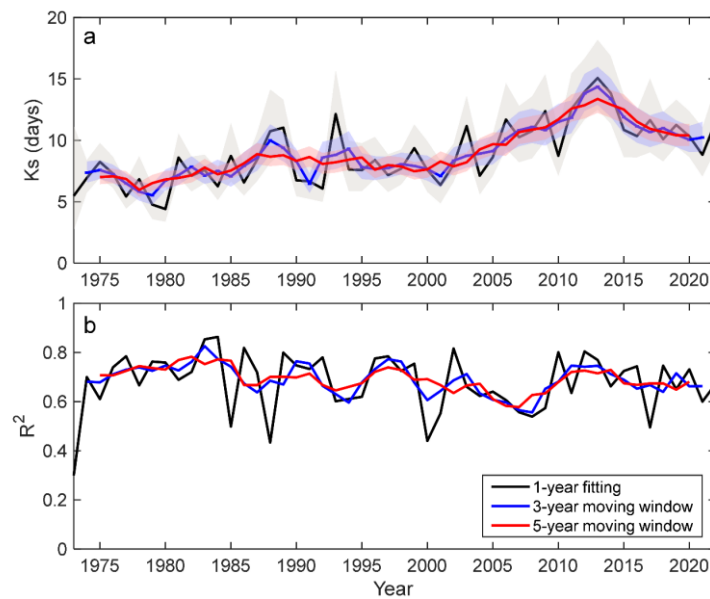


Figure S6 Time series of streamflow recession time constant (K_s) and model goodness-of-fit (R^2). (a) K_s time series derived from 1-year fitting (black line), 3-year moving-window fitting (blue line), and 5-year moving-window fitting (red line), with shaded areas representing the 95% confidence intervals. (b) Goodness-of-fit (R^2) of K_s estimates obtained using 1-year fitting (black line), 3-year moving-window fitting (blue line), and 5-year moving-window fitting (red line).

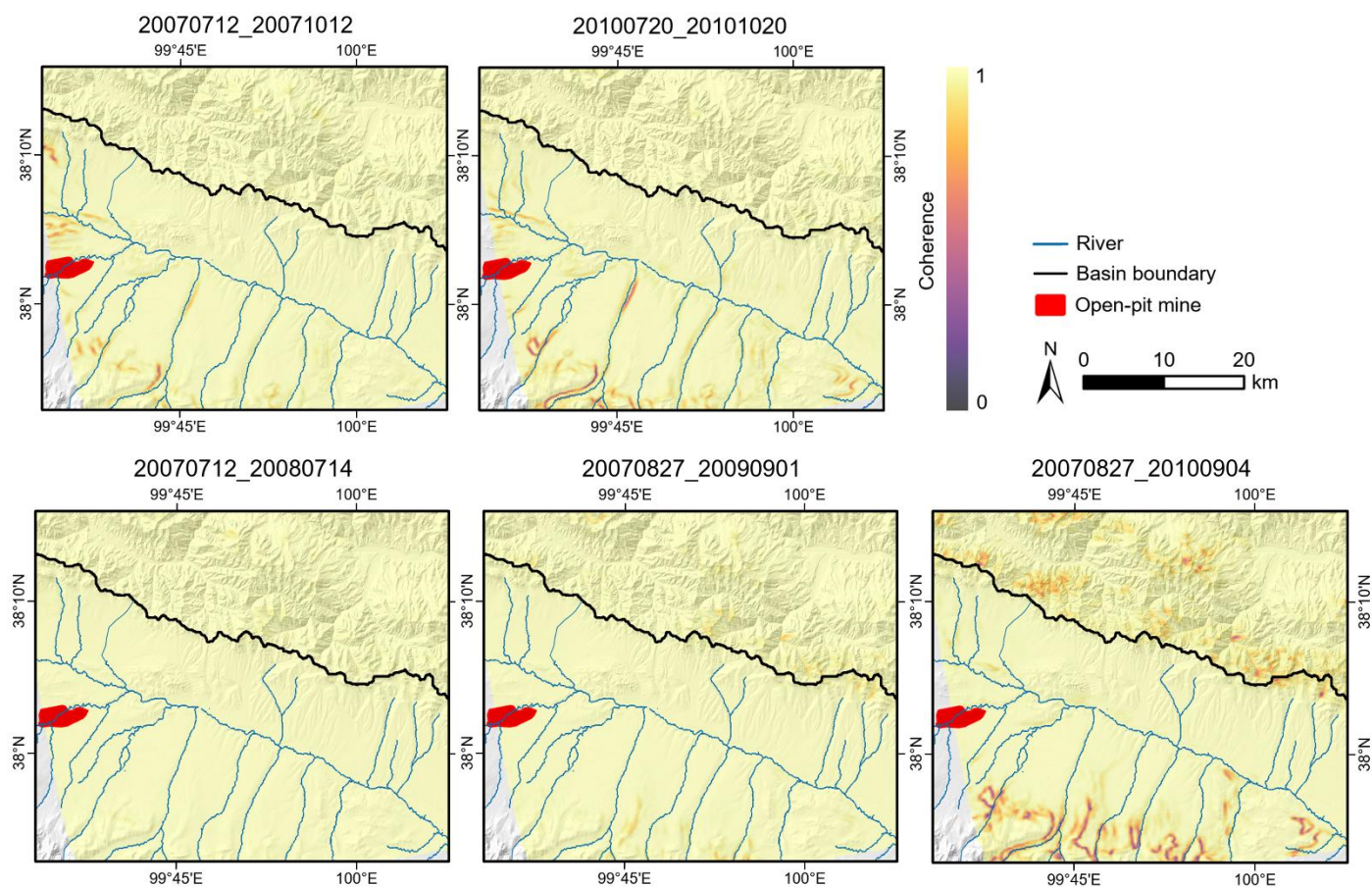


Figure S7 The coherence maps of the interferograms from ALOS-1.

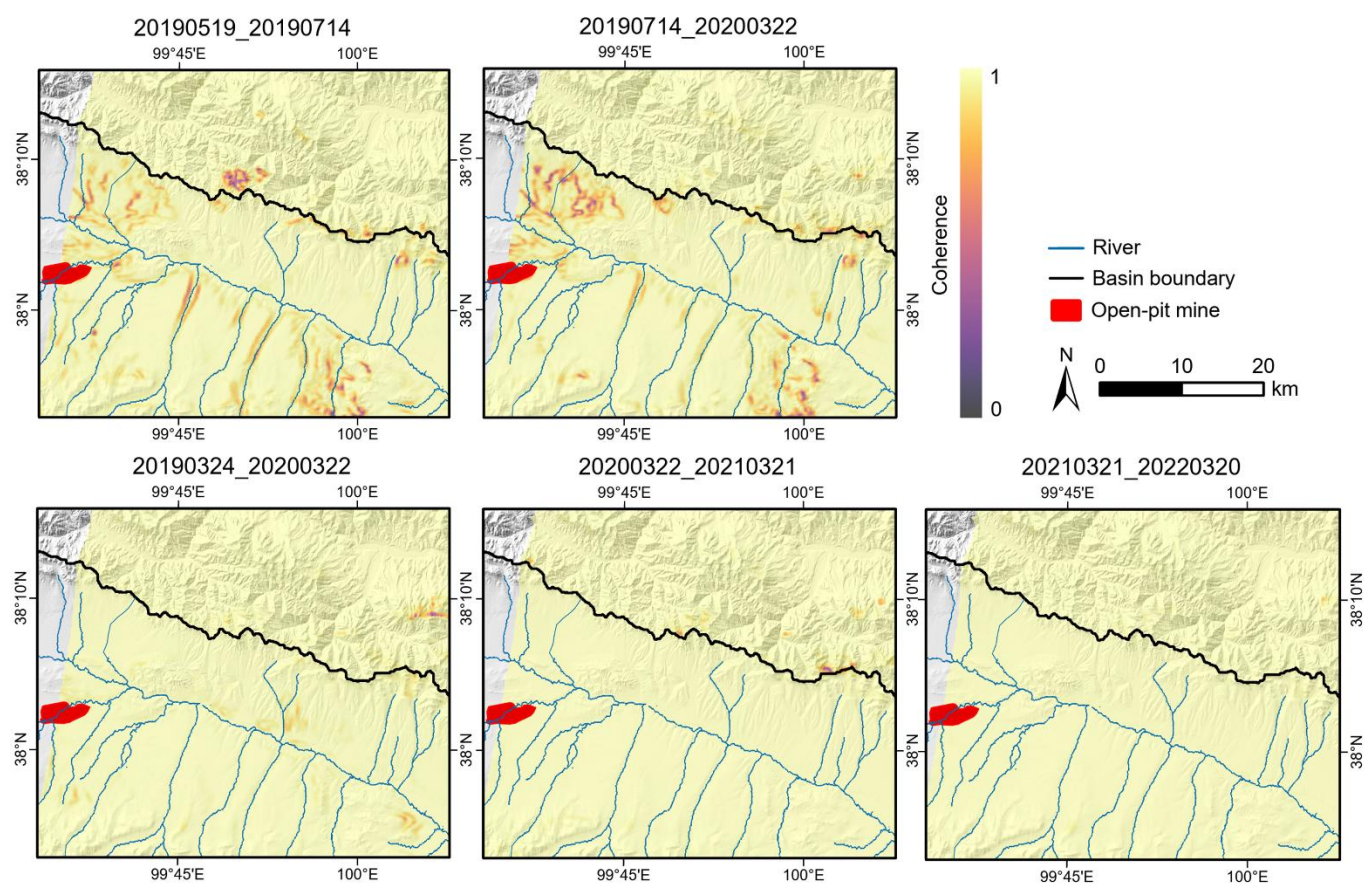
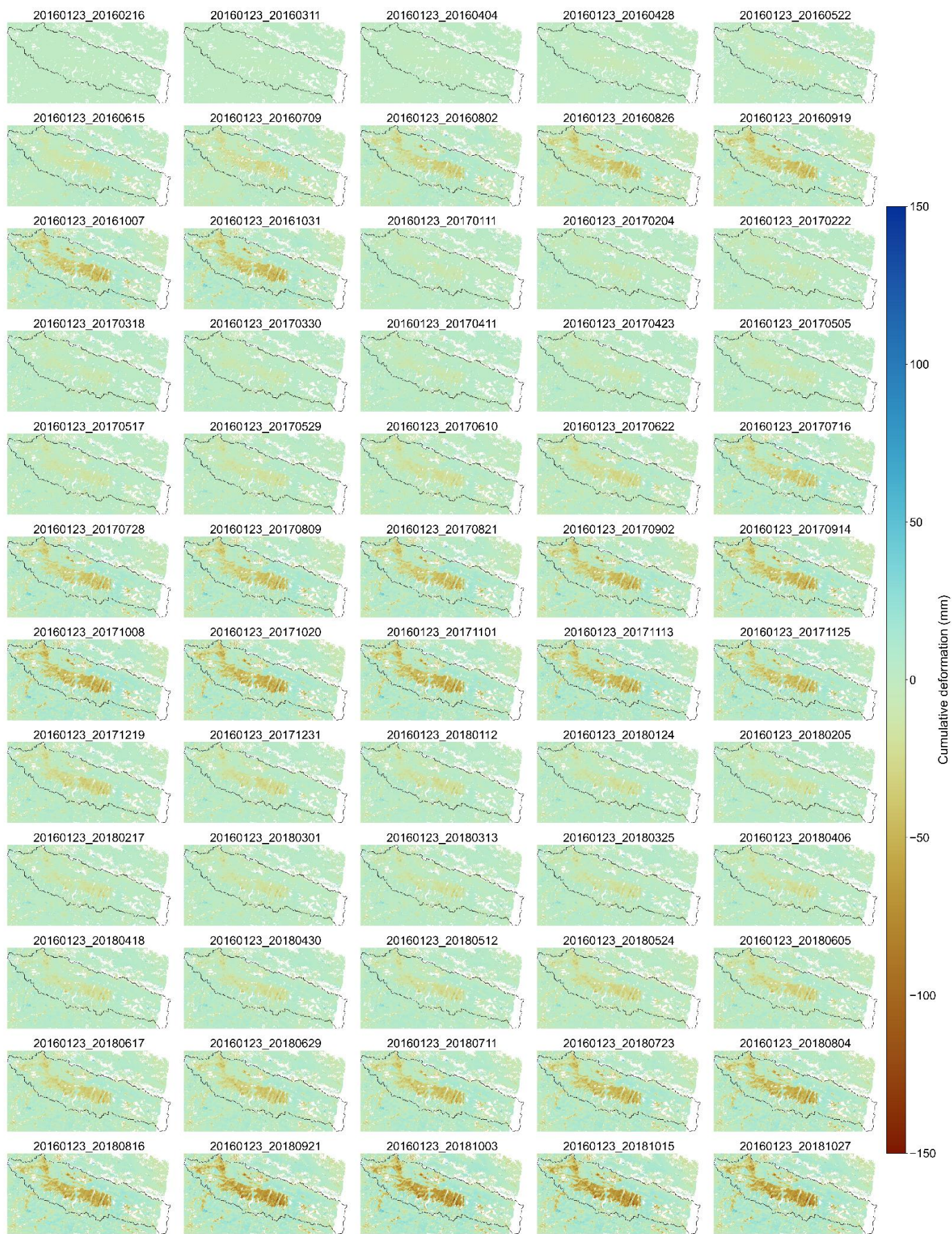
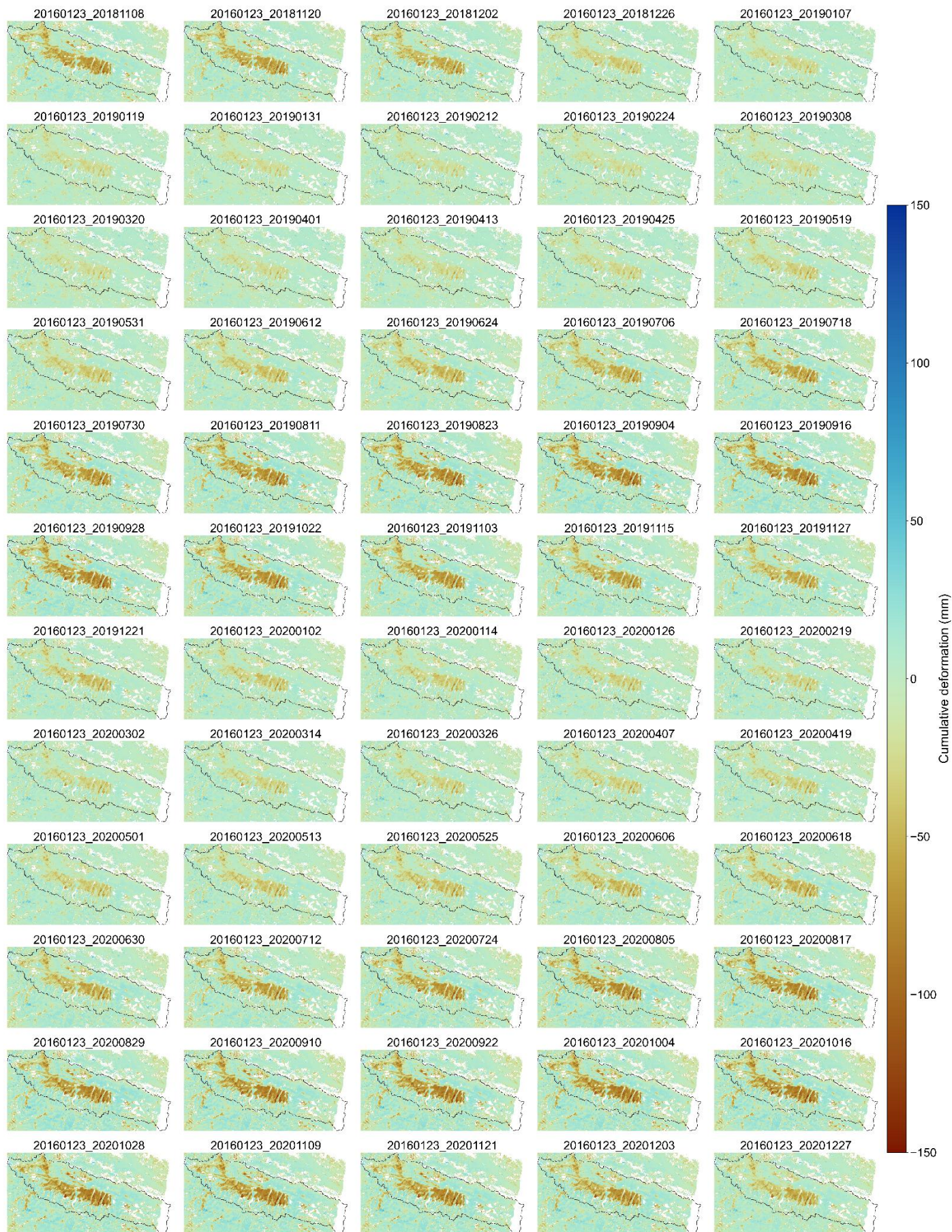


Figure S8 The coherence maps of the interferograms from ALOS-2.





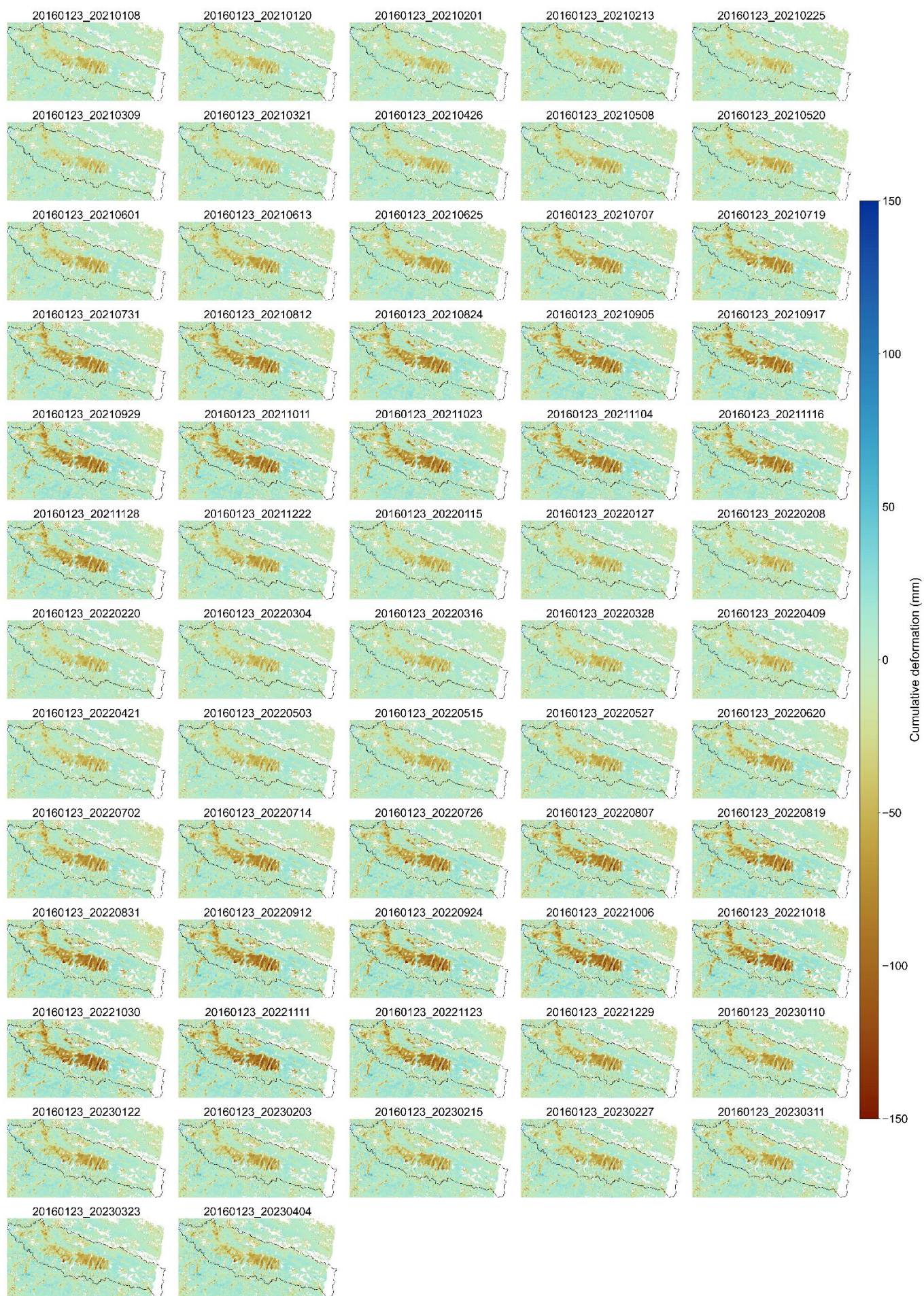


Figure S9 Time series of cumulative surface deformation from 2016 to 2023, referenced to the first acquisition date.

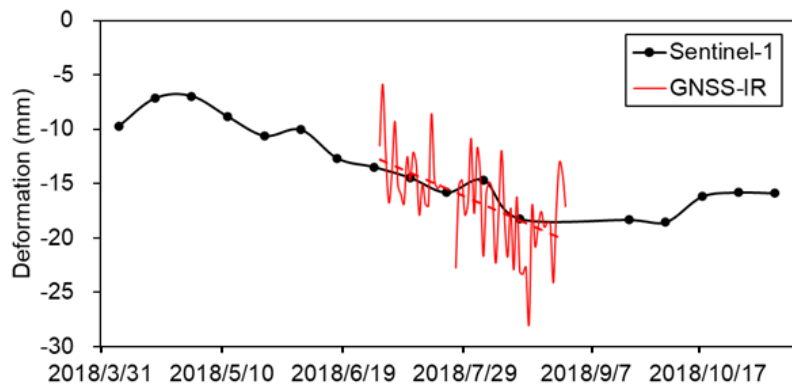


Figure S10 Comparison between Sentinel-1 InSAR deformation time series and GNSS-IR (GNSS Interferometric Reflectometry) measurements (Zhang et al., 2021) at the Yakou station during the snow-free period in 2018.

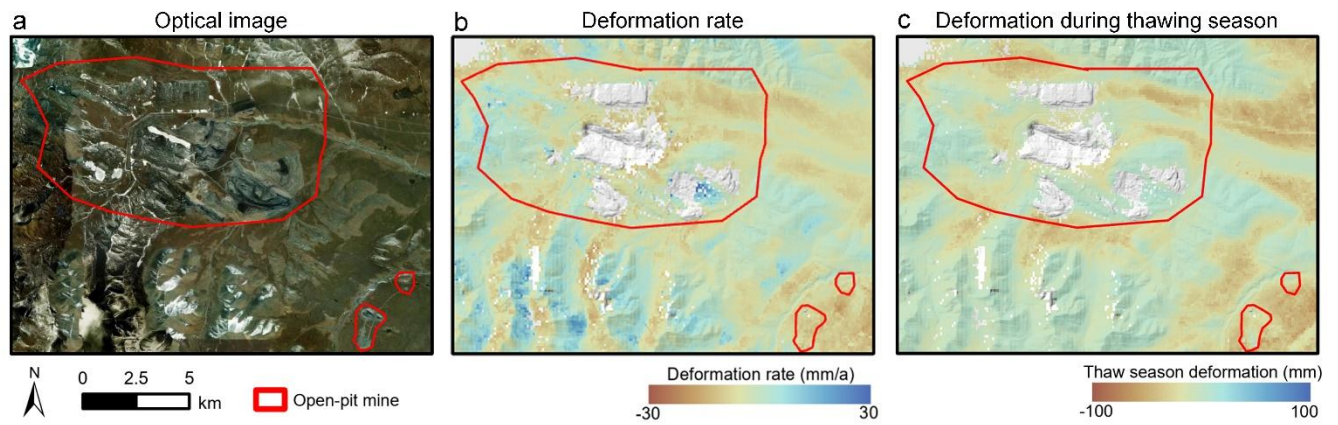


Figure S11 (a) Optical image of the open-pit mine in the western study area from Esri | Powered by Esri. (b) Deformation trend and (c) thaw-season deformation in its surroundings.

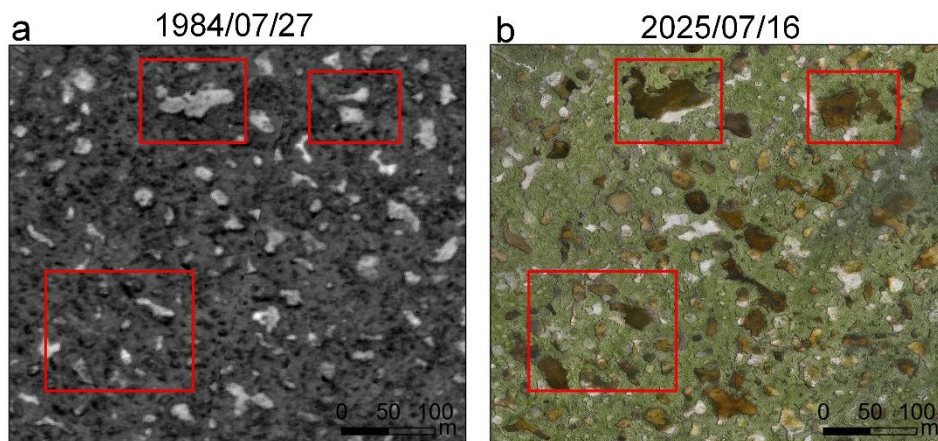


Figure S12 Comparison of ground surface characteristics at the P1 site near the Jiangcang open-pit mine on July 24, 1984 from Keyhole-9 data provided by the U.S. Geological Survey (a) and on July 16, 2025 from UAV data acquired by the authors (b).

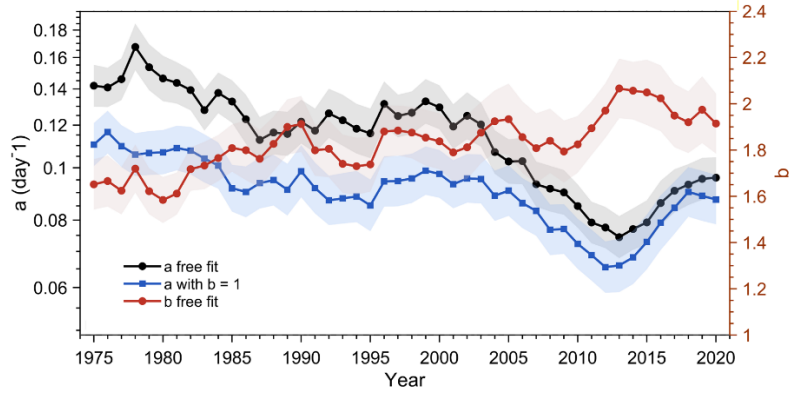


Figure S13 Time series of recession rate (a) fitted from the free- b recession model, a fitted from the constrained model with b fixed to 1, and the time series of recession parameter b . Shaded areas indicate the 95% confidence intervals.

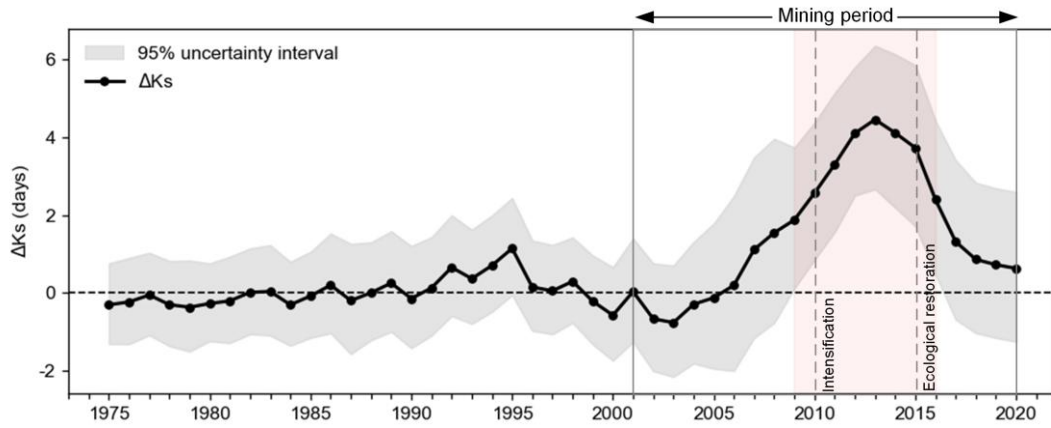


Figure S14 Climate-unexplained residual of the streamflow recession time constant (ΔK_s) and its 95% uncertainty interval. ΔK_s was calculated as the difference between the in situ-derived and climate-predicted recession time constants. The 95% uncertainty interval was conservatively propagated from the uncertainty bounds of both estimates. The red shading highlights periods when ΔK_s and the lower bound of its 95% uncertainty interval both exceed zero.

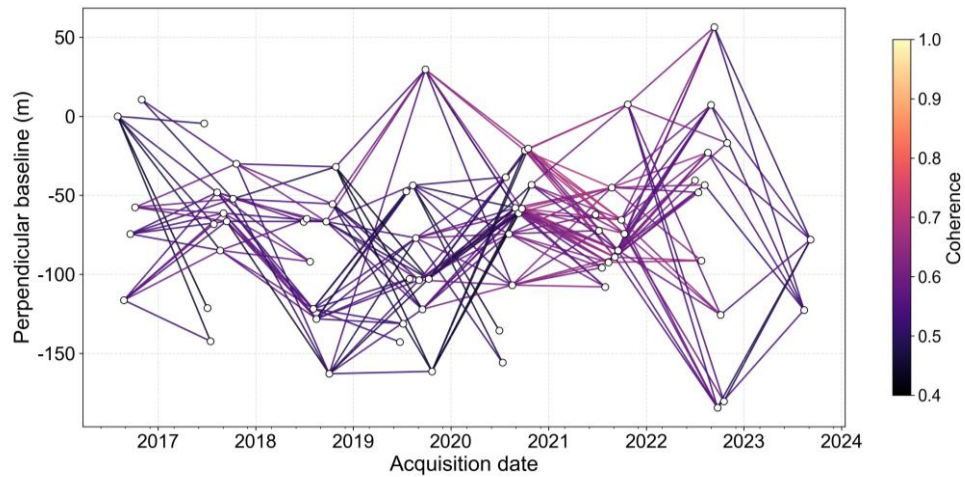


Figure S15 The network of the interannual Sentinel-1 interferograms acquired near the end of the thawing season, colored using the spatial mean coherence.

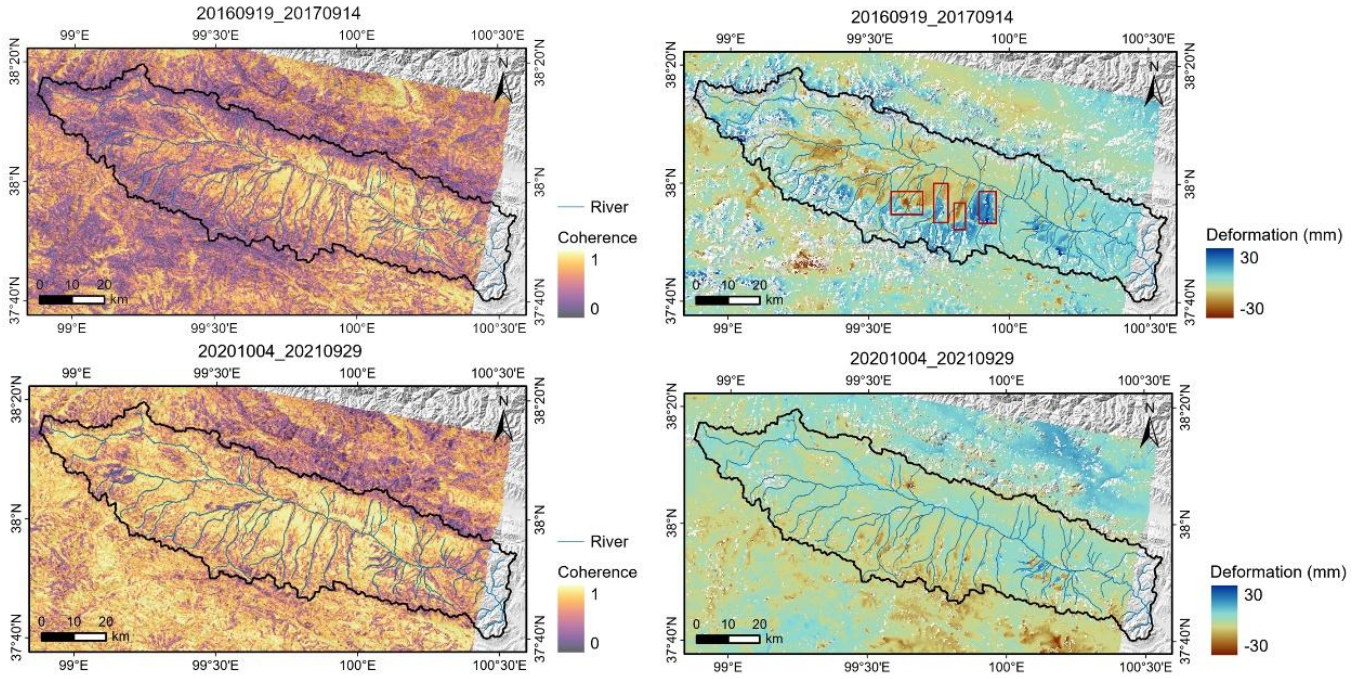


Figure S16 Coherence and deformation maps of representative interannual Sentinel-1 interferograms selected for their relatively high coherence. The red boxes indicate localized abrupt deformation discontinuities and sign reversals associated with likely phase unwrapping errors. The interferograms were generated using the Alaska Satellite Facility HyP3 processing service.

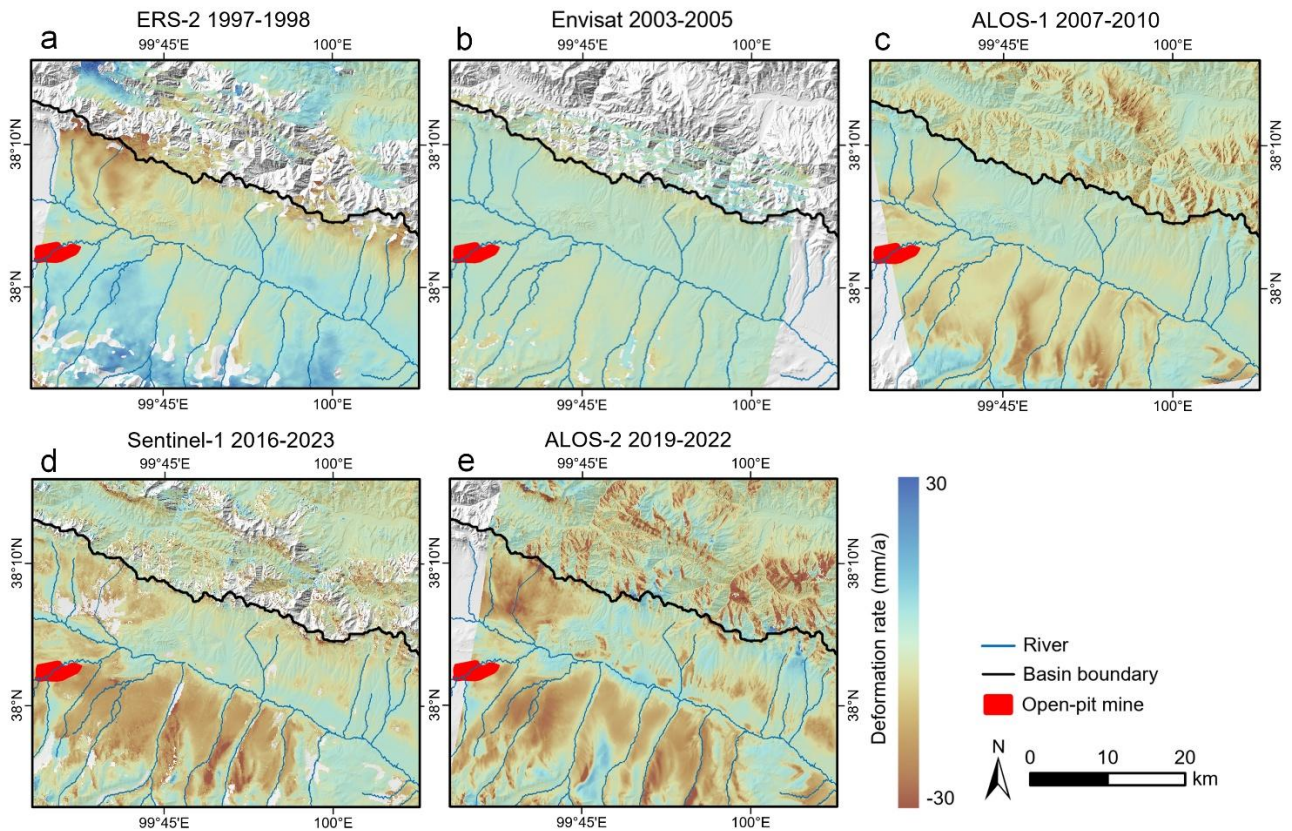


Figure S17 Vertical deformation rate maps during different periods derived from multi-source SAR data.

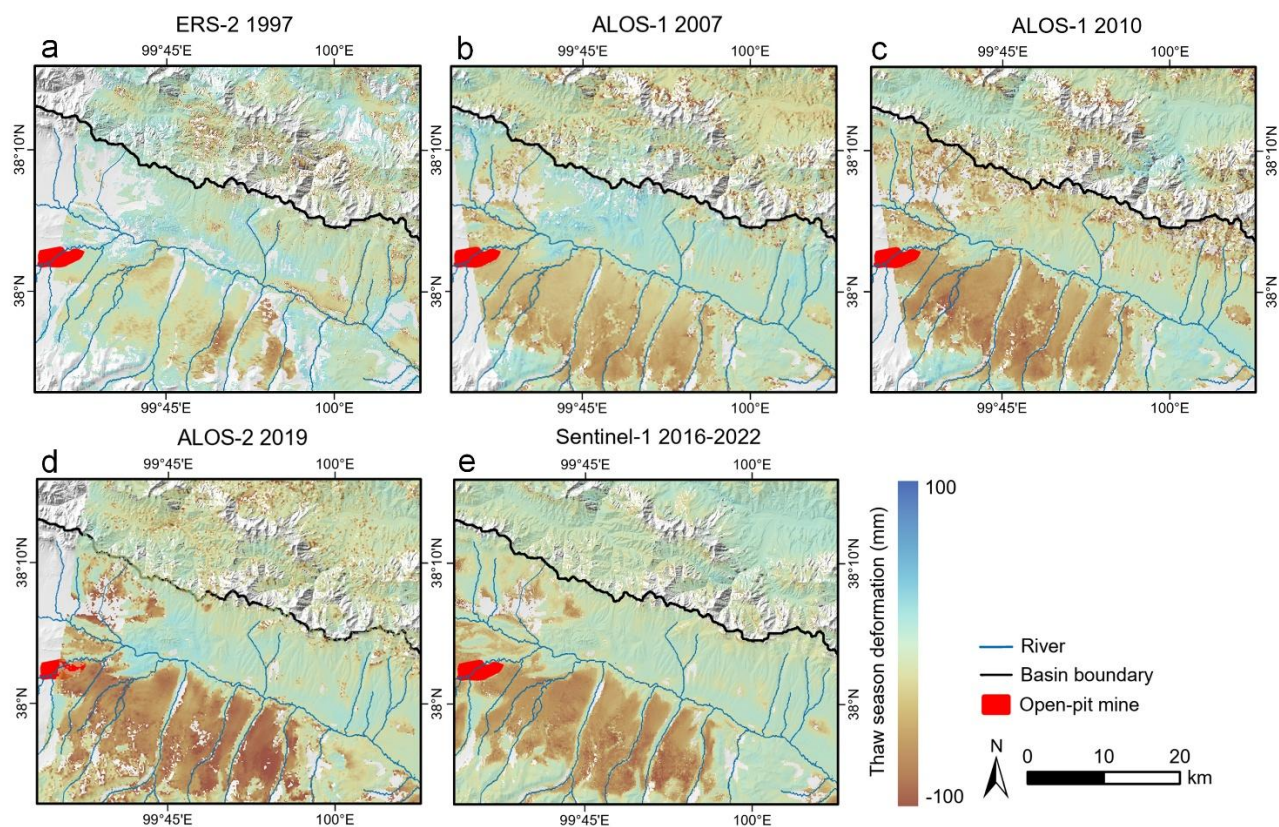


Figure S18 Vertical thaw-season deformation maps during different periods derived from multi-source SAR data.

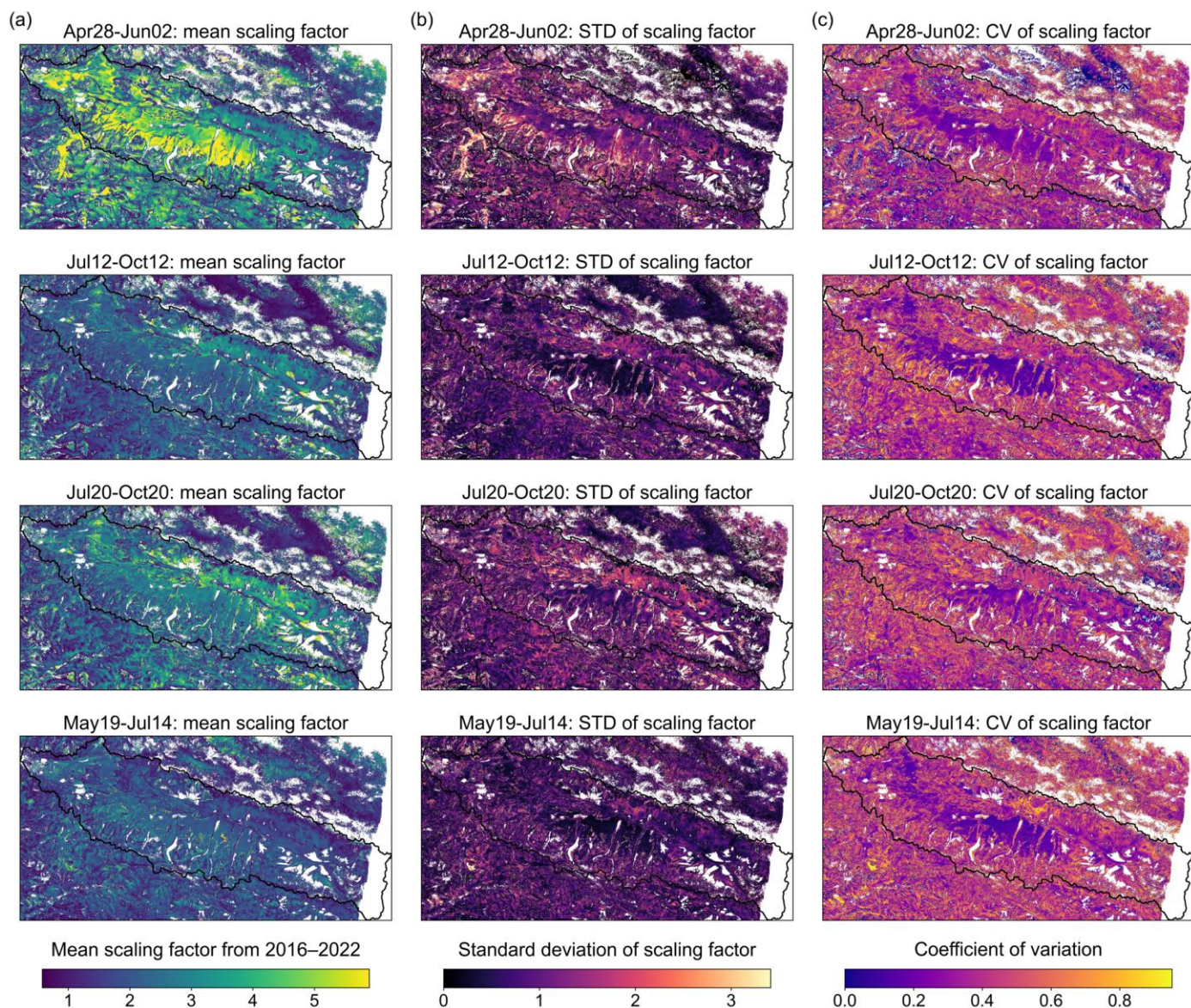


Figure S19 Spatial variability and uncertainty of the thaw-season deformation scaling factors derived from the Sentinel-1 time series during 2016–2022. (a) temporal mean, (b) temporal standard deviation (STD), and (c) coefficient of variation (CV) for the four sub-periods.