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Contents

Mapping and Monitoring of Slow-Moving Landslides in Upper Mustang (Nepal) Using Optical Images Correlation and InSAR

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Abstract:

Upper Mustang (Nepal) is a dry, high-altitude (>3000 m) sedimentary valley located between the high peaks of the Himalayas (Annapurna, Dhaulagiri) and the Tibetan plateau, destabilized by numerous large-scale slope deformations. Although these landslides have been recognized for a long time, their characteristics (location, extent, volume, speed, etc.) have never been systematically studied.

This project aims to determine the extent and kinematics of the slope deformations in Upper Mustang and evaluate their temporal and spatial controls using a combination of two remote sensing methods: Optical Images Correlation and InSAR. We use the correlation of very high-resolution Pleiades images (2013-2025) and InSAR of Sentinel-1 data to do an exhaustive inventory of the landslides. We generate time series of displacement with: PlanetScope images (2016-2025) for specific areas of slow velocity (from cm/y to m/y) and Sentinel-1 data (2014-2025) for areas with very slow velocity (mm/y to cm/y).

The results highlight the complementarity of InSAR and optical image correlation for mapping and monitoring deformations in Upper Mustang, which has so far enabled the detection of 85 landslides covering 42 km^2, representing 4.5% of the study area. The speeds of the landslides range from 5mm/yr to 3.3m/yr. Their temporal evolution varies, with some areas showing slow and linear evolution (western Gayu) and others showing trends toward acceleration and deceleration (Dhe, eastern Gayu), which could point to different triggering and controlling factors (climate, human activity, geology).

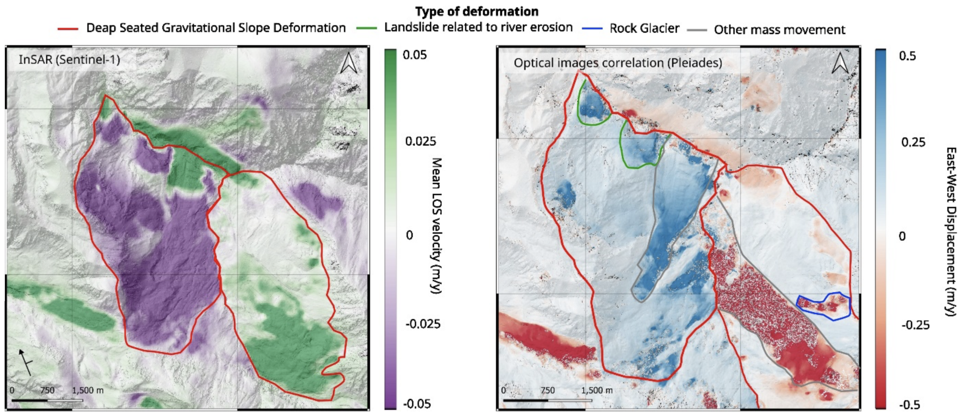

Figure 1: Complementarity of InSAR (left) and Optical Images Correlation (right) to detect different slope deformations in Upper Mustang (Gayu-Kharka area). InSAR (Sentinel-1, 2014–2025) is sensitive to very slow velocity, highlighting the deep-seated motion (red) of the two mountain slopes. Optical Image Correlation (Pleiades, 2013–2025) highlights the different types of landslides moving faster (m/y): the small deformations related to the river erosion (green), the rock glacier (blue) at the top of the deformation, and other slow-moving areas not yet related to a specific factor (grey)

30+ Yrs of Satellite-based Monitoring of Slow-moving Landslides in Central Nepal using Pixel Tracking

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Abstract:

The Himalayan Mountain hillslopes are affected by numerous and varied landslides. A specific type of landslide develops within the fragmented mass of old slided hillslopes. Associated displacement can reach several tens of mm/year, with potential high spatial and temporal variabilities, controlled by external factors including earthquake and monsoon. To understand the underlying dynamics and relationships between the displacement and external factors, the capability to monitor displacements over a large spatial and time range, as well as in difficult acquisition setups (high slopes, clouds and varying atmosphere) is needed. However, the upper range of displacement of these landslides reaches the application limits of commonly used methods such as InSAR, and cloud cover reduces the availability of optical images.

Here we demonstrate, in the Bhote Koshi Valley (Central Nepal), the capability of retrieving such displacements using both radar (Sentinel-1, PAZ) and high-resolution optical (Pléiades) image pixel tracking, and we present preliminary results on the dynamics of monitored landslides.

We found that pixel tracking of Sentinel-1 images needs large rectangular correlation windows and is better constrained both spatially and in amplitude using a frequency refinement. Preprocessing the images with a mask based on the amplitude dispersion index can further decrease the overall noise and blunders in adjacent areas. The perpendicular baseline does not impact the image's global errors, but can hinder signal detection in specific zones. Correlation is well preserved even for high temporal baselines, underlying smaller displacement values with higher S/N, and is therefore preferred for time series inversion. The minimal detected gradient is estimated around 1/6th of the pixel size (for Sentinel-1), higher than the threshold commonly agreed for pixel tracking of 1/10th. Furthermore, over the monitored area, the Bolde landslide shows a constant displacement to the North of 1–2 m/y at least since 1992 until now. The Tapgaon landslide, which shows no continuous displacement detectable by Sentinel-1 pixel tracking, exhibited a strong response to the 2015 Mw 7.8 Gorkha earthquake with more than 11 m of westward displacement. Pleiades' disparities show large displacement over the Bolde village and neighbouring farming fields, with displacement ranging from 0.27 m/y to 1.11 m/y to the North and divided into separate blocks. Decorrelation is observed at the river interface, highlighting high erosive flux.

This work shows that Sentinel-1 radar image pixel tracking can be crucial as it bridges the gap between InSAR and optical correlation, and allows landslides monitoring over large areas with high temporal coverage.

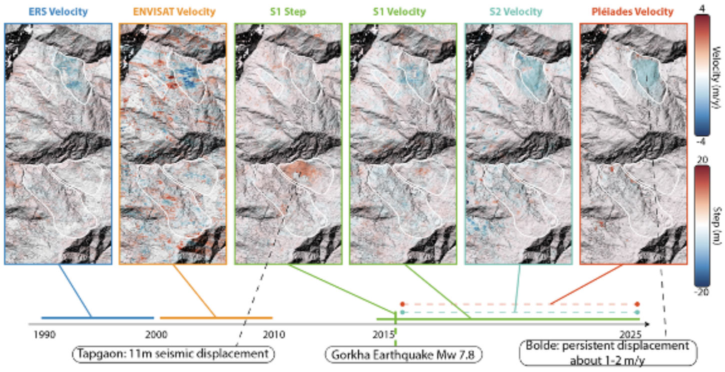

Figure 2: Continuous northward displacement of the Bolde landslide between 1992 and 2025 and the 2015 earthquake's response of the Tapgaon landslide

Improving the reliability of InSAR time series in periglacial environments using FLATSIM products

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Abstract:

The Tibetan Plateau is characterized by extensive periglacial landscapes. In such environments, seasonal freezing and thawing of the uppermost ground layer result in cyclic surface movements driven by expansion and contraction associated with water phase changes. On slopes, the regolith cover responds to these freeze–thaw cycles, generating slow downslope mass movements (mm/yr) known as solifluction. With ongoing climate warming, ground freezing conditions are evolving, impacting these processes and potentially leading to slope destabilization through rapid failure. Remote sensing provides an opportunity to monitor such movements using InSAR. Based on Sentinel-1 acquisitions, the CNES–ForM@Ter FLATSIM products offer a unique opportunity to monitor and map these processes on a large scale.

However, in such environments, rapid changes in soil moisture and ground heave can lead to unwrapping errors when the unwrapping path crosses areas with high phase gradients, potentially inducing 2π ambiguities in the unwrapped phase. Moreover, rapid variations in soil moisture introduce a systematic phase component, particularly in short temporal baseline interferograms, which biases SAR time series. Here, we present the processing strategies we use to mitigate these two issues, in order to minimize phase aliasing and biases in InSAR time series over periglacial terrains using FLATSIM products. The first correction is applied prior to the critical phase unwrapping step, where a seasonal deformation model, derived from the raw FLATSIM product, is subtracted from the interferometric phase to reduce phase variability in areas with strong phase gradients. After unwrapping the reduced phase, the seasonal model is added back to each interferogram to reconstruct the full unwrapped signal. To mitigate bias, short temporal baseline interferograms are excluded, and the remaining interferograms are weighted by their temporal baseline during the time-series analysis. Overall, this strategy enhances the reliability of InSAR time series in periglacial environments, providing robust data for monitoring periglacial dynamics and their evolution across the Tibetan Plateau.

Unstable Slopes and Shifting Landscapes: Slow-moving landslides in the East African Rift

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Abstract:

Human activities are transforming tropical mountain landscapes at unprecedented rates through deforestation, agricultural expansion, and urbanization. These changes amplify the frequency and magnitude of geo-hydrological hazards such as landslides. While shallow, rapid landslides are well documented, the controls on the activity and dynamics of large, slow-moving landslides (SML) remain much less understood, despite their persistent impacts on communities and sediment dynamics.

This study demonstrates how the combined use of radar and optical Earth observation data enables the detection, mapping, and monitoring of deep-seated landslides across vast and remote tropical regions such as the Albertine Rift. By mapping and comparing more than 100 active and 3,000 historical landslides distributed along the 1,500 km Rift branch, we reveal how climatic, lithological, tectonic, and anthropogenic factors jointly control their occurrence.

We further analyse multi-year landslide dynamics across contrasting environments, supported by unique ground-based validation datasets built on years of fieldwork in the region, and provide detailed insights into failure mechanisms of recent catastrophic landslides in the area. Altogether, this work delivers a unique regional-scale assessment of SML activity in tropical environments and highlights how human-driven land use changes can modulate their behaviour. It offers new perspectives on how environmental transformations shape landscape evolution, geo-hydrological hazards and sediment transfer in rapidly changing mountain regions.

Multi-Mission PSInSAR Assessment of Long-Term Ground Deformation Processes in Belgium

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Abstract: Ground deformation linked to land subsidence and post-mining uplift represents a growing environmental and geotechnical concern in Belgium. Using Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) analyses based on more than thousand SAR images from ERS-1/2, ENVISAT, TerraSAR-X and Sentinel-1A satellites, this study investigates the spatial and temporal evolution of ground movements over the past three decades. Results highlight several main regions affected by measurable vertical ground motion. The Scheldt estuary and harbour area of Antwerp exhibit subsidence rates up to 3.4 mm/year, mainly driven by the compaction of Holocene alluvial sediments and heavy industrial loading. In West Flanders, a 45 × 25 km subsidence bowl shows average velocities between −1 and −2.9 mm/year, caused by overexploitation of the Landenian and Cambrian aquifers. Around Merchtem, 20 km northwest of Brussels, PSInSAR time series reveal alternating phases of subsidence and uplift related to groundwater extraction and subsequent aquifer recharge in the Cambro-Silurian formations exploited by local industries. In contrast, former coal mining basins in Limburg (Campine) and Hainaut demonstrate progressive uplift following mine closure and flooding of underground workings. Velocities reach up to +18 mm/year in Limburg, reflecting rapid hydrostatic rebound, while lower values in Hainaut correspond to slower post-closure recovery. These observations emphasize the dual anthropogenic origin of land deformation in Belgium—subsidence from groundwater withdrawal and compaction, and uplift from mine water rebound. The study confirms the efficiency of PSInSAR for long-term, low-amplitude deformation monitoring in a temperate, densely urbanized environment. It provides critical insights for urban planning, groundwater management, and risk mitigation associated with geotechnical and hydrogeological processes.

Recent satellite-based radar and optical monitoring of the activity of retrogressive slow-moving landslides in Nepal during monsoon

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Abstract:

The steep Himalayan slopes are highly exposed to landslides, primarily triggered by earthquakes and intense monsoon precipitation. Along the southern slopes of the Himalayas, a specific type of landslide affects old destabilized hillslopes, characterized by intense internal fracturing and prone to rapid retrogressive erosion through deep gully incision, ultimately leading to the catastrophic collapse of secondary landslides. Understanding these mechanisms requires establishing potential spatio-temporal relationships between landslide units and triggering factors, such as rainfall, increased groundwater pressure, or gully erosion, as well as their influence on displacement amplitude. In this study, high-resolution optical and radar satellite remote sensing data have been integrated to characterize the dynamics of three regressive slow-moving landslides located in the Marsyangdi and Khudi valleys in Nepal. The combination of DSM comparison and optical pixel tracking provides a comprehensive view of the three-dimensional surface displacement fields across the landslides, insights into their geometries, and highlights how gully downcutting drives landslide activity through basal destabilization. The high-temporal-resolution displacements derived from SAR amplitude images, along with their correlation with precipitation and groundwater table variations, reveal a non-linear response to the monsoon. This process begins with the destabilization of the basal panel, followed by large displacements in the main panel driven by fluctuations in the water table. This unique dataset highlights the influence of river erosion on hillslope dynamics and the relationship between the deformation of three slow-moving landslides and water table variations during the monsoon season.

Giant collapses of high Himalayan peaks and their impact on the Himalayan landscapes

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Abstract:

Although the topographic evolution and erosion dynamics of the Himalayan range have been extensively documented, it is not known how the very high Himalayan peaks erode. Some conceptual models assume that intense periglacial processes involve regressive erosion of high peak headwalls at rates dictated by valley-floor downcutting of glaciers. However, recent data indicate that frost-cracking intensity decreases with elevation, suggesting instead that the highest Himalayan peaks are nearly free of erosion, raising the question of their long-term evolution. Here, we report geological evidence for two Holocene giant rockslides that occurred in the Annapurna Massif (central Nepal), involving total rock volumes of approximately 23 and 18 km^3, respectively, and that decapitated high paleosummits, most probably culminating above 8000 m for the first one. Our data demonstrate that the main mode of high-altitude erosion could be catastrophic mega-rockslides, leading to the sudden reduction of high peaks by several hundred meters and ultimately preventing the Himalayan summits from growing indefinitely (Lavé et al., 2023). This erosion mode, associated with steep slopes and high relief, arises from a higher mechanical strength of the high-peak substratum, probably due to the presence of permafrost at high altitude and the absence of bedrock weathering. In addition to their direct impact on the evolution of the High Himalayan landscape and ridgeline, giant rockfalls can also have major implications for the evolution of downstream rivers and natural hazards through massive sediment supply, though this effect mainly depends on the rockfall location within the range.

Keywords: Giant rockslides, high Himalayan summits.

Reference: Lavé, J. et al. (2023). *Medieval demise of a Himalayan giant summit induced by mega-landslide. Nature*, 619(7968), 94–101. DOI: 10.21203/rs.3.rs-1918601/v1.

Shaped by landslides – how interacting tectonics, lithology and urbanisation define slope stability in Bukavu and the Ruzizi Gorge (DR Congo)

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Abstract:

Landslides are geo-hydrological hazards that both shape landscapes and pose significant risks to communities. Despite their widespread impacts, the geomorphological and geological factors controlling their occurrence are often not well understood. This is especially so in mountainous tropical regions where environmental conditions, such as bedrock type and soil weathering can be specific. This research investigates the influence of these factors on landslide activity in the tropical African environment of the Ruzizi Gorge and the adjacent city of Bukavu, which ranks among the world's most exposed urban areas to landslide hazards. By reconstructing the geomorphological evolution of the landscape and combining UAV, optical and SAR remote sensing data, we examine how slow-moving landslides occur and evolve in this region. Our findings highlight the roles of river incision and weathering as key controls, while also revealing the significant impact of urbanisation on slope instability. We conclude by discussing the implications of these findings for assessing risks associated with slow-moving landslides in this complex and evolving environment.

Field Deployment of a Multi-Instrument Monitoring Network for "SLIDE" project in Nepal: Technical and Community Insights

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Abstract:

Monitoring slow-moving landslides requires continuous, high-quality geophysical and environmental data collected directly from unstable slopes. As part of the "SLIDE" project in Nepal, we deployed a network combining geophones, broadband seismometers, GNSS stations, and two meteorological stations to study the slow-moving landslide near the village of Bolde.

As the field engineer responsible for the installation phase, I will present the practical aspects of deploying and maintaining these instruments in remote Himalayan terrain. Each system required specific installation techniques and careful site selection to ensure stable measurements and long-term performance. Field operations were challenged by difficult access, variable road conditions, limited power availability, and unpredictable weather. Transporting fragile equipment to steep and isolated locations often relied on local porters and improvised logistics. A particular challenge was installing 14 stations in just one week, in addition to the 3 stations already in place, requiring careful planning, efficient coordination, and rapid adaptation to on-site constraints.

Heavy and bulky equipment was purchased locally, while scientific instruments and accessories were shipped from Luxembourg, requiring careful advance planning to minimize unforeseen issues on site. Beyond technical challenges, community engagement proved essential to the project's success. Close collaboration with local residents guided several site choices and ensured the protection and maintenance of the stations over time.

Preliminary results focus on data recovery and quality assessment. The quality of the GNSS and meteorological data, as well as initial interpretations related to the landslide, will be presented. This presentation highlights the lessons learned from deploying a complex multi-sensor network in challenging field conditions, emphasizing the importance of local cooperation and adaptive engineering in long-term landslide monitoring.

Figure 3: Seismic station deployed on the Bolde landslide, central Nepal, showing the broadband sensor, solar power system, and GNSS antenna.

Monitoring slow-moving landslides with seismic sensors: Preliminary insights from an instrumental deployment on a km-scale landslide in Nepal

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Abstract:

Satellite methods offer unrivalled spatial coverage of surface displacements on a weekly scale. However, they do not directly provide details of deformation at depth, nor do they offer sufficient temporal resolution to elucidate the continuity or intermittent nature of the landslide deformation during phases of heavy rainfall, strong rise in the water table or during intermediate seismic shaking. To address these issues in the context of the ANR/FNR project "Slide", we have recently deployed in late October 2025 a geophysical network (seismic sensors + GNSS receivers) at the level of one active landslide in Nepal ("Bolde landslide") previously identified by satellite methods. Two stations have been installed in May 2025 and one additional monitoring station has been deployed in a neighbouring landslide ("Tapgaon"), which moved significantly following the Gorka earthquake in April 2015 but has remained quite stable since then.

In this presentation, we show the very first data and preliminary analyses from the deployment of 13 short-period 3-components (3-C) seismic nodes (SmartSolo) and 3 broadband 3-C seismometers (Nanometrics Trillium Compact) inside and outside the Bolde landslide to form a network (+1 broadband seismometer in Tapgaon). One aspect of this so-called passive seismic survey relies on the analysis of the seismic ambient noise continuously recorded by 3-C sensor(s) to infer changes in the landslide's properties (i.e., weakening, reconsolidation) with time, e.g. following rainfalls or large earthquakes. If multiple sensors are used, spatial changes can be studied. Additionally, the same network of seismic sensors in Bolde allows to locate microseismicity in the area associated to creeping events along the failure planes (i.e., low magnitude seismicity not felt by humans). In complement to the measurements of ground deformation provided by the co-located GNSS stations, the seismic signals (e.g., slope quakes, tremor) provide information on how the deformation propagates at depth, whether it affects the entire slip plane simultaneously or more restricted areas, leading to a better understanding of the rupture dynamics and the construction of a model that can potentially predict the evolution of the slip along the failure plane.

Slow-Moving Landslides in Central Nepal: Strategy for Mass Processing of InSAR Time Series

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Abstract:

This presentation will outline the methodology and processing strategy designed to analyze large batches of SAR images over the Central Nepal region, an area characterized by complex terrain and dynamic environmental conditions. The study addresses the challenges posed by the vast volume of SAR data, diverse acquisition modes, steep Himalayan topography, dense vegetation, seasonal variations, and the high velocity of ground displacement. To overcome these challenges, we developed an automated processing chain using the AMSTer Toolbox (Derauw et al., 2020 ; d'Oreye et al., 2021; Smittarello et al., 2022). This chain is capable of handling extensive Sentinel-1 archives (as well as ERS, ENVISAT, TSX, PAZ, ALOS… for smaller portions of the region) and rapidly processing new data provided as soon as they become available. The processing chain is also preprared for the upcoming NISAR L-Band mission. SAR images are read and transformed into a native format (consistent across all sensor types). Several combinations of interferometric pairs are then selected based on various Perpendicular (Bp) and/or Temporal baseline (Bt) criteria. Each selected interferometric pair is processed to generate, among other results, a geocoded displacement map using a grid common to all acquisitions. Finally, all deformation maps are inverted using the MSBAS method (Samsonov and d'Oreye, 2012) to extract the mean linear velocity maps and deformation time series in Line of Sight (LoS) and/or vertical and horizontal components. The entire process is fully automated, computationally optimized, and self-evaluating, from data download up to the display and sharing of results on a dedicated webpage. Given the rapid deformation rates observed, our approach emphasizes the use of short spatial baselines. While this introduces a risk of bias from fading signals (Ansari et al., 2021), we evaluate the trade-offs involved. We will explore the impact of different Bp/Bt selection criteria on the quality of the InSAR time series results, and assess the effect of coherence threshold filtering on the ground deformation time series. Additionally, the presentation will evaluate the effectiveness of ionospheric, geodetic, and tropospheric corrections in refining displacement measurements and improving geocoding, utilizing Sentinel-1 ETAD products (Gisinger et al., 2022). We will also investigate the feasibility of 3D inversions (Samsonov et al., 2020) for selected landslides to provid deeper insights into their kinematics. The processed data are structured and made accessible to support future development and application of Machine Learning-driven tools in landslide detection, tracking, and monitoring.

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Geo-hydrological hazard risks in changing tropical Africa: natural or human-induced processes?

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Abstract:

The changing climate is affecting the frequency and intensity of rainfall-triggered geo-hydrological hazards (GH) such as flash floods, landslides and gully erosion. These hazards are also influenced by human-induced land transformations such as deforestation and urbanization. GH events often co-occur and interact, leading to cascading and compound hazards with amplified impacts. In the future, the frequency and/or severity of GH events are expected to rise, not only as a result of climate change and land transformation but also due to population growth and expanding exposure to disasters. Tropical regions, in particular, are environments often characterized by data scarcity and remain under-researched with respect to GH processes. In Africa, high and rapidly increasing population densities, combined with elevated societal vulnerability, make these regions disproportionately exposed to GH impacts. In this study, we assess the influence of land transformation and climate on the occurrence of GH risks in tropical Africa. We adopt a holistic and transdisciplinary approach that integrates extensive fieldwork, satellite remote sensing, historical archive analysis, climate data collection, citizen science and awareness-raising tools. Our findings demonstrate the role of human activities and climate on the spatial and temporal patterns of GH risks in both rural and urban environments. Overall, we emphasize the importance of considering the human context when investigating GH processes in regions under anthropogenic pressure, as this is essential for improving hazard prediction, understanding disaster dynamics, and anticipating the effects of global change.

Birth and removal of a landslide dam in a controlled tropical river gorge

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Abstract:

Landslide dams extend the reach of landslide hazards by impounding upstream water, setting the stage for catastrophic outburst floods, and disrupting river dynamics, discharge, and sediment transport. Although their geomorphic and societal consequences can be long-lasting, the mechanisms governing their formation and evolution remain poorly constrained. In most settings, rapid river adjustment or extreme triggering events obscure these processes. Located in the Ruzizi Gorge at the DR Congo–Rwanda border, the Lukula landslide dam offers a rare opportunity to isolate landslide–river interactions in a system where hydropower infrastructure imposes strong controls on discharge and sediment transport.

Using a 70-year archive of aerial and satellite imagery, we show that the Lukula landslide, likely initiated within the last ∼10,000 years during gorge incision, experienced decades of slow movement before a two-year acceleration phase led to successive collapses in February and March 2024 — without clear seismic or meteorological triggers. The resulting dam impounded approximately 7 million m^3 of water, forming a lake that is now receding as the Ruzizi River incises the deposit. Twelve 3D models from UAS surveys and satellite data reveal post-failure dynamics. Despite ∼220,000 m^3 of toe erosion, landslide motion (up to 35 m in one year) remains confined to the upper slope, suggesting weak coupling between fluvial erosion and slope deformation. In contrast, multispectral satellite data show strong coupling between landslide erosion and downstream sediment flux. Lukula provides a rare, well-documented example of the birth and removal of a landslide dam in a hydrologically controlled tropical river gorge.

Dynamics and controls of a tropical slow moving landslide measured by remote sensing: the study case of Grand Éboulis, Réunion Island.

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Abstract:

Slow-moving landslides can cause significant infrastructure damage and casualties, making their monitoring a critical societal challenge. In the context of climate change and the projected intensification of rainfall extremes, understanding the response of slow-moving landslides to extreme meteorological conditions is essential. However, ground-based surveys are often difficult. In this study, we associate radar interferometry and optical imagery to investigate the dynamics of a remote tropical slow-moving landslide on Réunion Island, Grand Eboulis, and its relationship with precipitation regimes. Our approach enables us to retrieve (1) the bi-monthly dynamics of the Grand Eboulis landslide from cumulative displacement maps and ground deformation time series derived from Sentinel-1B images and (2) its multi-annual dynamics from optical aerial images. Between 2016 and 2021, the landslide moved eastward and downward at rates of up to 14 cm/yr and 9 cm/yr, respectively. Displacement was punctuated by periods of accelerated motion following an exceptionally wet season in mid-2018. In contrast, two slower periods coincided with the 2018 dry season combined with an exceptionally arid 2019, and with a prolonged drought in 2020. Additionally, between 2017 and 2019, shallow failures were mapped only in 2018 at the landslide front and were attributed to Cyclone Dumazile. This study suggests that slow-moving landslides may respond to seasonal contrasts by modulating their continuous displacement and to extreme events through shallow failures. The combined use of InSAR and remote sensed optical imagery proved to be efficient for studying such a type of events and can easily be widely applicable.

Large-Scale InSAR Processing and Machine Learning for Himalayan Slow-Moving Landslide Detection: Integrating Mass Data Processing, Climate Modeling, and High-Performance Computing

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Abstract:

Mapping slow-moving landslides across the Himalayas to quantify their contribution to long-term erosion requires processing massive volumes of satellite radar data. SAR satellites like Sentinel-1 can measure ground displacement at millimeter precision, but analyzing thousands of freely available images spanning multiple orbital tracks presents computational challenges.

Multi-temporal InSAR techniques extract deformation signals from these archives, while modern deep learning architectures like U-Net and YOLOv8 enable automated landslide detection. High-performance computing infrastructure becomes essential: processing tens of thousands of interferograms demands parallel CPU workflows, while training neural networks requires GPU acceleration.

This presentation examines large-scale InSAR processing approaches and their integration with regional climate modeling (specifically MAR) to understand monsoon-driven landslide dynamics. I discuss how DInSAR expertise, climate modeling experience, and HPC infrastructure combine to address the challenge of systematic landslide mapping at broad scale the SML activity and velocity in central Nepal.

Linking Ground Deformation to Subsurface Anisotropy: Integrating InSAR, PDE Modeling, and Bayesian Inference

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Abstract:

Groundwater is the hidden lifeline of our planet — yet understanding how it moves beneath our feet remains a major scientific challenge. In fractured aquifers, water doesn't flow uniformly but follows preferential pathways shaped by cracks and faults, creating anisotropy. In this work, we explore how InSAR (Interferometric Synthetic Aperture Radar) observations of ground deformation can reveal these hidden flow directions. Using a 3D poroelastic finite element model of the Anderson Junction aquifer (Utah), we show that anisotropic hydraulic conductivity (AHC) produces a distinct, elliptical displacement signature detectable by InSAR. To move beyond deterministic modeling, we construct a stochastic prior model of the AHC tensor that quantifies uncertainty in both fracture orientation and magnitude. Building on this, we develop a Bayesian framework that couples Firedrake (for PDE simulation) with NumPyro (for probabilistic inference). Our results demonstrate the promise of remote sensing–driven inversionas a next-generation approach for characterizing and managing aquifers.

Assesing Earth's crustal deformation through GNSS network analysis: insights from Iran and the Luxembourg permanent GNSS network

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Abstract:

Global Navigation Satellite Systems (GNSS), including the GPS, GLONASS, Galileo, and BeiDou, provide precise positioning, navigation, and timing (PNT), and critically, geodetic monitoring of crustal deformation. Using Precise Point Positioning (PPP), GNSS time series can resolve station positions and provide valuable information about the Earth's deformation and associated processes. Given the importance of GNSS networks for monitoring ongoing crustal deformation, we analyze two networks: (i) a 14-station GNSS network in southwestern Iran, and (ii) Luxembourg's permanent network (SPSLux), consisting of 6 stations distributed across the country. GNSS observations from the Iranian network are processed with PRIDE-PPPAR, while SPSLux data are processed with GROOPS. For SPSLux, we estimate positions and velocities in the local north, east, and up (NEU) components over 1 August 2006-31 December 2020. SPSLux stations exhibit consistent horizontal motion with mean velocities of ∼18 mm/year east and 15 mm/year north, implying a northeastward motion consistent with the rigid motion of the Eurasian plate relative to North America. Long-term vertical rates are small (0.5 mm/year uplift), superimposed on pronounced seasonal signals: monthly-smoothed time series show minima of ∼-10 mm near the start of each year and maxima of ∼+10 mm in spring, consistent with hydrological loading. At Walferdange, a cumulative upward displacement exceeding 40 mm by early 2020 is observed, suggesting local processes in addition to seasonal loading. For southwestern Iran, station positions and velocities were first estimated for the period from 9 December 2015-24 May 2016. The stations exhibit northeastward motions, with mean velocities of ∼32.23 mm/yr east and 28.97 mm/yr north. We then inverted the GNSS velocities for two- dimensional strain and rotation using the Spakman and Nyst approach, discretizing the region with 51 triangles and 32 model nodes. This method yields spatially variable deformation rates that are independent of prior geological or geophysical constraints, providing new insights into present-day surface kinematics. These results demonstrate the value of PPP-based GNSS time series for quantifying plate motion, seasonal mass loading, and regional strain, thereby improving our understanding of the coupled tectonic–hydrological behavior of the Earth system.

Numerical modeling of Mt Merapi 2020 instability crisis

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Abstract:

The western flank of Merapi volcano (Java, Indonesia) moved from July 2020 to January 2021. The cliff collapses at the summit, the size of the affected area (about 500 m in elevation and 118 km wide) and a flank displacement of about 14 m, never observed before, led to fears of a flank collapse. Field observations suggested a correlation between this flank movement and the opening of a NE–SW fracture crossing the entire summit, filled with magma. In the present study, we developed numerical models based on the discrete element method (DEM) to investigate the role of the NE–SW fracture pressurization on the deformation of Merapi. Even though simplified considering the complexity of the processes at stake, our approach enables us to reproduce the observed deformations both in terms of kinematics and kinetics. It shows that the deformation was inelastic and affected the western flank to a depth of about 500 m below the summit. Under the pressure of the magma within the fracture, the western flank tilted slightly, causing its sliding with displacement magnitudes increasing with elevation. As observed in the field, the sliding eventually stopped so that the flank reached a new stable state, demonstrating how topographic readjustments of a volcano, driven by magma pressure, can produce significant plastic deformation without leading to major instabilities.

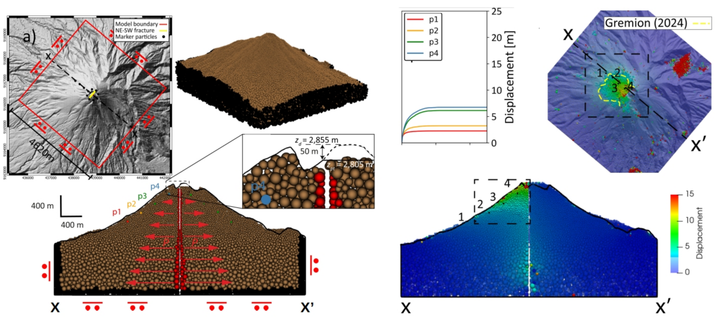

Figure 4: 3D DEM model of Mount Merapi: numerical setup (left), displacement field (right).

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Imaging the Invisible: Seismic Tomography Reveals Earth's Hidden Structure and Dynamics

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Abstract:

Understanding how the Earth deforms and evolves requires looking beneath its surface — into regions that cannot be observed directly. Seismic tomography offers this unique window, transforming seismic waves into three-dimensional images of the subsurface. Beyond mapping variations in seismic velocity, recent advances allow us to detect anisotropy — directional dependence of wave speed — which encodes information about rock fabric, deformation, and stress. Here, we introduce the fundamental concepts of seismic tomography and anisotropy. We highlight how these methods reveal both the structure and the dynamics of the lithosphere and upper mantle. Using examples from regional to local scales — from active convergent margins to volcanic environments — we show how tomographic models illuminate the processes shaping our planet's interior. By integrating seismic imaging with other geological and geophysical observations, we can bridge deep and shallow processes, linking subsurface dynamics to the observable evolution of the Earth. Seismic tomography thus emerges not only as a tool for imaging structure, but also as a way to visualize the living dynamics of the Earth.