

# The DRIAR Project: Dry-Rifting In the Albertine-Rhino Graben, Uganda

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## Abstract

Continental rifting is a critical component of the plate tectonic paradigm, and occurs in more than one mode, phase, or stage. While rifting is typically facilitated by abundant magmatism, some rifting is not. We aim to develop a better understanding of the fundamental processes associated with magma-poor (dry) rifting. Here, we provide an overview of the NSF-funded Dry Rifting In the Albertine-Rhino graben (DRIAR) project, Uganda. The project goal is to apply geophysical, geological, geochemical, and geodynamic techniques to investigate the Northern Western Branch of the East African Rift System in Uganda. We test three hypotheses: (1) in magma-rich rifts, strain is accommodated through lithospheric weakening from melt, (2) in magma-poor rifts, melt is present below the surface and weakens the lithosphere such that strain is accommodated during upper crustal extension, and (3) in magma-poor rifts, there is no melt at depth and strain is accommodated along pre-existing structures such as inherited compositional, structural, and rheological lithospheric heterogeneities. Observational methods in this project include: passive seismic to constrain lithospheric structure and asthenospheric flow patterns; gravity to constrain variations in crustal and lithospheric thickness; magnetics to constrain the thermal structure of the upper crust; magnetotellurics to constrain lithospheric thickness and the presence of melt; GNSS to constrain surface motions, extension rates, and help characterize mantle flow; geologic mapping to document the geometry and kinematics of active faults; seismic reflection analyses of intra-rift faults to document temporal strain migration; geochemistry to identify and quantify mantle-derived fluids in hot springs and soil gases; and geodynamic modeling to develop new models of magma-poor rifting processes.

Fieldwork will begin in January 2022 and the first DRIAR field school is planned for summer 2022. Geodynamic modeling work and morphometric analyses are already underway.

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### SCIENTIFIC MOTIVATION

The DRIAR project was funded by the NSF Frontier Research in Earth Sciences in late 2020 to investigate continental rifting, which is a process integral to plate tectonic theory. As such, continental rifts have been intensely investigated to understand the physical processes that initiate and sustain continental break-up. The leading paradigm for rift initiation suggests "magma-assisted (wet)" rifting is required to weaken strong lithosphere such that only small tectonic stresses are needed for rupture to occur (e.g., Buck, 2004; Wright et al., 2006; Mulheath et al., 2016; Jones et al., 2019). However, numerous examples of "magma-poor (dry)" rifting exist worldwide that do not show surface expressions of magmatism and challenge the magma-assisted model.

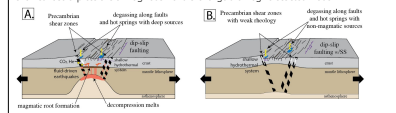


Figure 1. A. Conceptual model of magma-poor rifting with melt at depth. B. Model of magma-poor rifting with no melt at depth. Based on Mulheath et al. (2016, 2018).

### Hypotheses for magma-poor rift segments

- 1) Despite the lack of surface volcanism, melt is present at depth and has weakened the lithosphere, allowing for strain localization during the onset of rifting.
- 2) The lack of surface volcanism is indicative of a lack of magmatism at depth, and pre-existing structures weaken the lithosphere allowing.

### PROJECT OBJECTIVES

1. Use magnetotellurics (MT), gravity, and passive-source broadband seismology to determine lithospheric thickness, map the rigidity and density of the lithosphere, mantle-flow direction from deep anisotropy, potentially frozen lithospheric anisotropy, and to assess the presence or absence of melt at depth.
2. Use magnetic, gravity, and seismology to determine the thermal structure and thickness of the crust beneath the rift zone.
3. Constrain surface motions with new GNSS observations.
4. Collect geomorphic samples for Quaternary geochronology of landforms cut and offset by the rift-bounding and intra-basinal faults to determine their fault slip rates.
5. Conduct detailed field observations to examine the geometry and kinematics of rift related structures and pre-rift (Precambrian) structures. Use these observations to evaluate the extent to which the Precambrian structures have been reactivated during rift evolution and possible seismic risks of these structures.
6. Use industry seismic reflection data constrained by well data to investigate fault evolution, as well as, strain migration and evolution through time.
7. Use the geochemistry of hot springs and measurements of magmatic gas fluxes along faults and non-faulted areas to identify mantle magmatic signatures and their variability along strike, and to establish the presence or absence of shallow magma chambers and low fluid/volatiles assist faulting. Simultaneously, quantify the variability of tectonic  $\text{CO}_2$  flux to the atmosphere.
8. Use the helium isotope data from recent lavas and xenoliths from the rift axis to determine the magmatic sources beneath the northern Western Branch of the EARS.
9. Jointly use our observations to simultaneously determine temperature, density, and compositional heterogeneities, as well as, use these products as input to develop a new class of geodynamic models for magma-poor rifting.

### REFERENCES

Buck, W. R., 2004. Continental rifting: A review. *Journal of Geophysical Research*, 109, B04301. <https://doi.org/10.1029/2003JB002271>

### STUDY AREA

We test our hypotheses by studying the magma-poor northern Western Branch of the East African Rift System (EARS; Figure 2), which comprises the Lakes George-Edward Graben and the Albertine-Rhino Graben. This setting provides an unprecedented opportunity to study the hypothetical along-axis transition from wet (magma-assisted) to dry (magma-poor) rifting, and to rift termination.

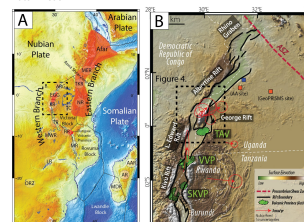


Figure 2. A. Map of the study area (Uganda) showing the East African Rift System (EARS) and the Albertine-Rhino Graben. B. Detailed map of the study area showing the rift axis, faults, and topographic features.

### FIELDWORK AND BROADER IMPACTS

The DRIAR team plans to initiate fieldwork in January 2022 with a temporary seismic deployment (PASSCAL), magnetotelluric observations, structural geologic fieldwork, campaign GNSS observations, and the installation of 4 new continuous GNSS stations (Figure 3). In summer 2022, we also plan to conduct the first of two field schools to train our African collaborators and a few US participants in the techniques that are being used for this project. The field school is part of our comprehensive broader impacts plan that encompasses capacity building, societally relevant scientific outcomes, communicating broadly our results through educational videos and open access data, and by providing professional development and mentoring guidance to students participating in the DRIAR project (Figure 4).



Figure 3. A map of the study area (Uganda) showing the locations of the 4 new continuous GNSS stations and the PASSCAL seismic deployment.




Figure 4. Diagram outlining the broader impacts components of the DRIAR project.

### ACKNOWLEDGEMENTS


This project is funded by the National Science Foundation Frontier Research in Earth Science Program (FRSE) through grant number 2014213 (Virginia Tech), 2021105 (Midwestern State University), 2021025 (Woods Hole Oceanographic Institution), 2021460 (University of Minnesota), 2021044 (University of California), 2021141 (Northwestern University), and 2021139 (University of Kansas). We are also receiving technical support from UNAFICO (USAID) and IRIS (NSF).




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VIRGINIA TECH




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UNIVERSITY OF LEICESTER




UNIVERSITY OF ICELAND



WOODS HOLE OCEANOGRAPHIC INSTITUTION



MSU



MAKERERE UNIVERSITY

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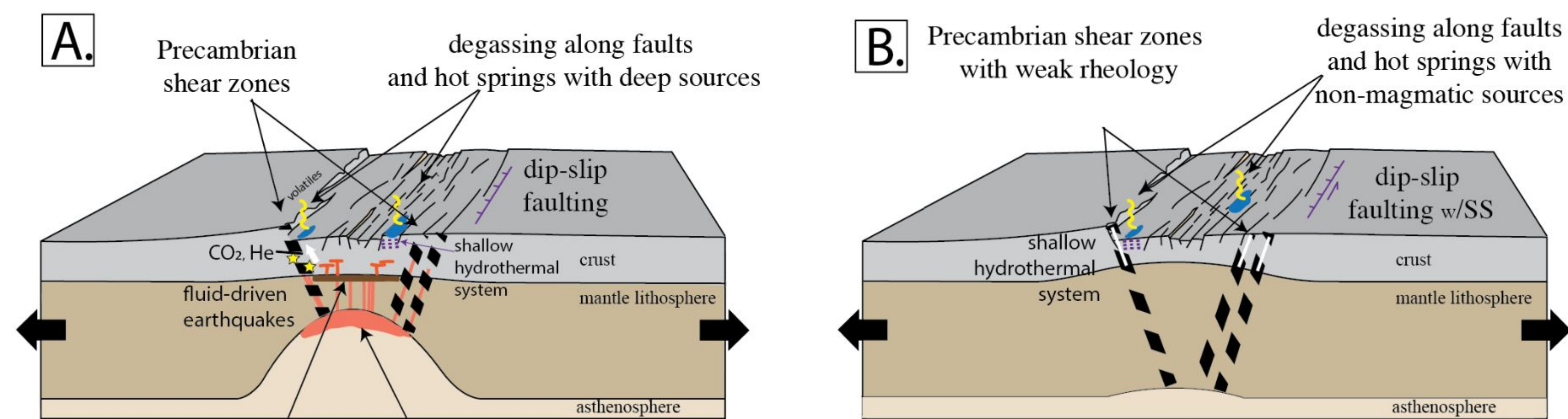


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## REFERENCES

- Buck, W.R., 2004. Consequences of asthenospheric variability on continental rifting. Rheology and deformation of the lithosphere at continental margins 62, 1-30.  
- Jones, J.R., D.S. Stamps, Christelle Wauthier, Juliet Biggs, Eifuraha Saria (2019), Evidence for slip on a border fault triggered by magmatic processes in an immature continental rift, Geochemistry, Geophysics, and Geosystems, doi: 10.1029/2018GC008165  
- Muirhead, J.D., Kattenhorn, S.A., 2018. Activation of preexisting transverse structures in an evolving magmatic rift in East Africa. J. Struct. Geol. 106, 1-18  
- Muirhead, J.D., Kattenhorn, S.A., Lee, H., Mana, S., Turin, B.D., Fischer, T.P., Kiang, G., Dindi, E., Stamps, D.S., 2016. Evolution of upper crustal faulting assisted by magmatic volatile release during early-stage continental rift development in the East African Rift. Geosphere 12, 1670-1700  
- Wright, T.J., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D., Stork, A., 2006. Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. Nature 442, 291-294, doi: 10.1038/nature04978. Geophysical Journal International, 205  
- Stamps, D.S., Saria, E. and Kreemer, C., 2018. A Geodetic Strain Rate Model for the East African Rift System. Scientific reports, 8(1), p. 732, doi:10.1038/s41598-017-19097-w  
- Stamps, D.S., C. Kreemer, R. Fernandes, T. Rajonariason, G. Rambolamanana (2021), Redefining the Kinematics of the East African Rift System, Geology, https://doi.org/10.1130/G47965.1

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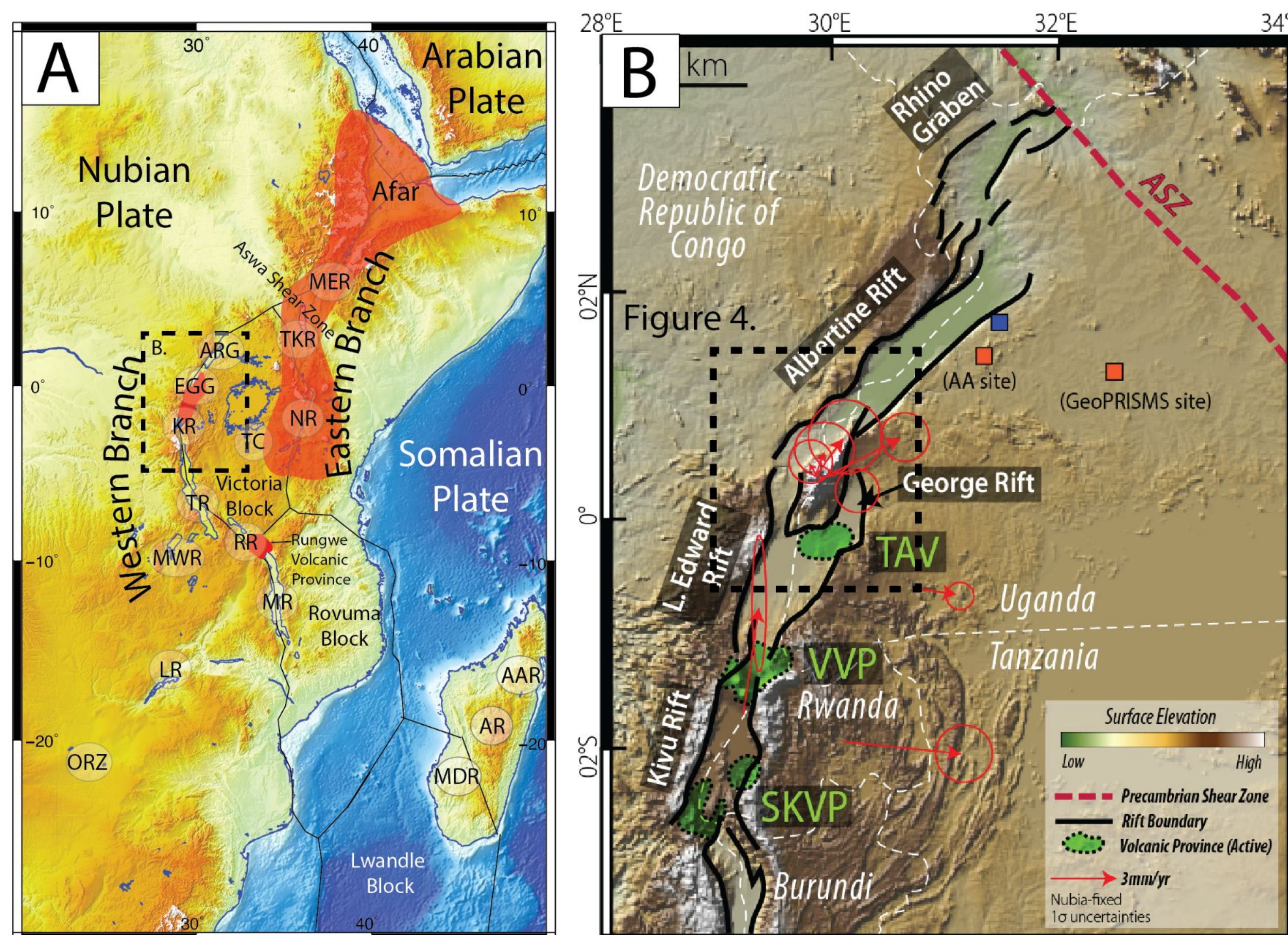


Figure 2: (A) Active rifts and key features of the EARS. Red zones are approximate zones of magma-assisted rifting. Hashed lines are zones of deformation from Stamps et al. (2021). MER = Main Ethiopian Rift. EGG = Lakes Edward-George Graben. ARG = Albertine-Rhino Graben. TC = Tanzania Craton. MWR = Mweru Rift. TKR = Turkana Rift. NR = Natron Rift. AAR = Alaotra-Ankay Rift. AR = Ankaratra Rift. MDR = Morondava Rift. RR = Rukwa rift. MR = Malawi Rift. LR = Luangwa Rift. ORZ = Okavango Rift Zone. (B) GPS velocity solution from Stamps et al. (2018) showing new campaign and continuous GNSS sites as blue and orange squares, respectively. This work entails using these new sites. Quaternary volcanoes as green triangles. TAV = Toro-Ankole Volcanic Field. VVP = Virunga Volcanic Province.

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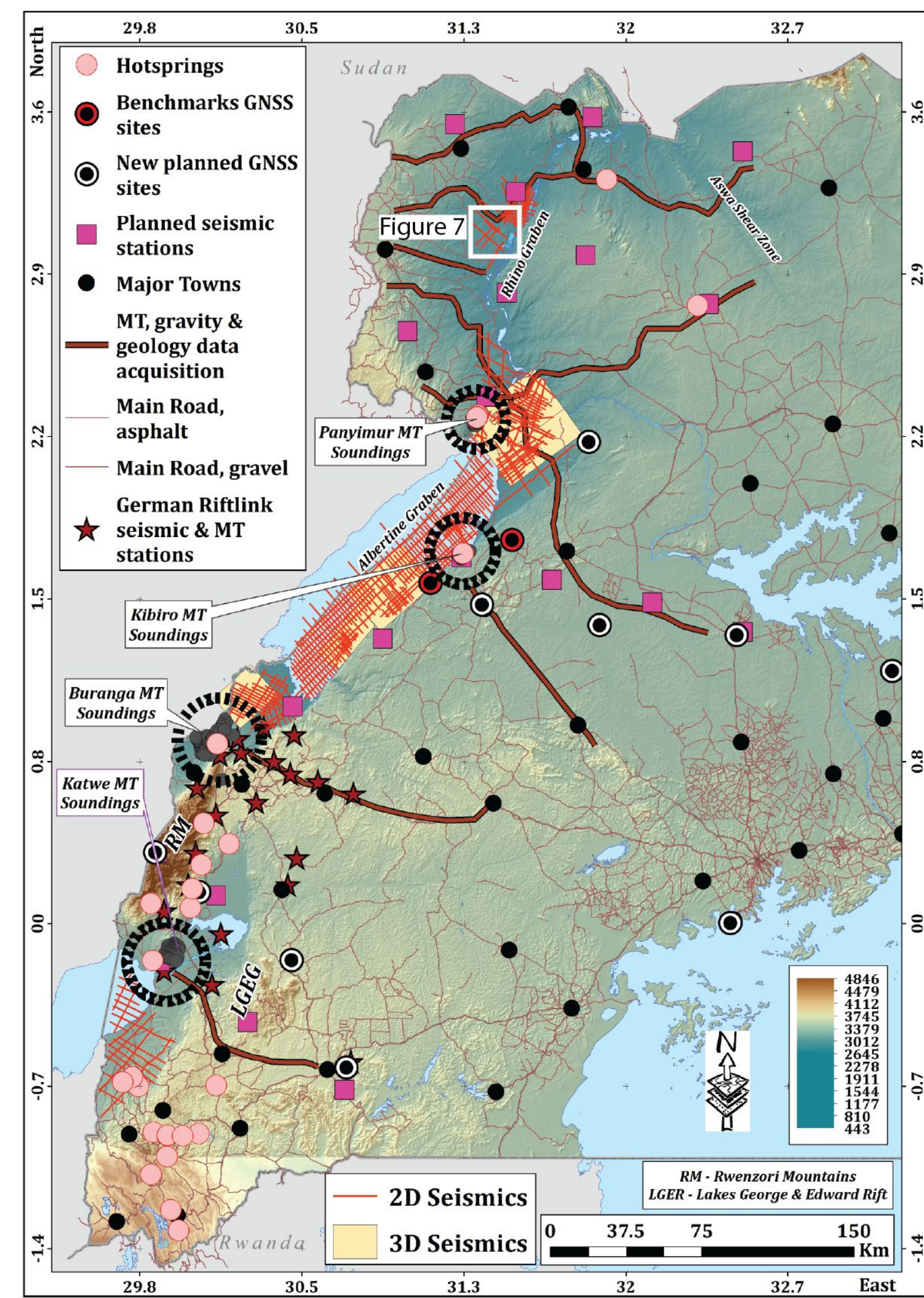


Figure 3. A map of the study area (only in Uganda) showing topography, hot springs, streams, lakes, and major towns. Also shown are proposed transects for the acquisition of geological and geophysical data and seismic profiles. Where possible, the transects will also be used to collect gas samples in addition to samples taken at hot springs.

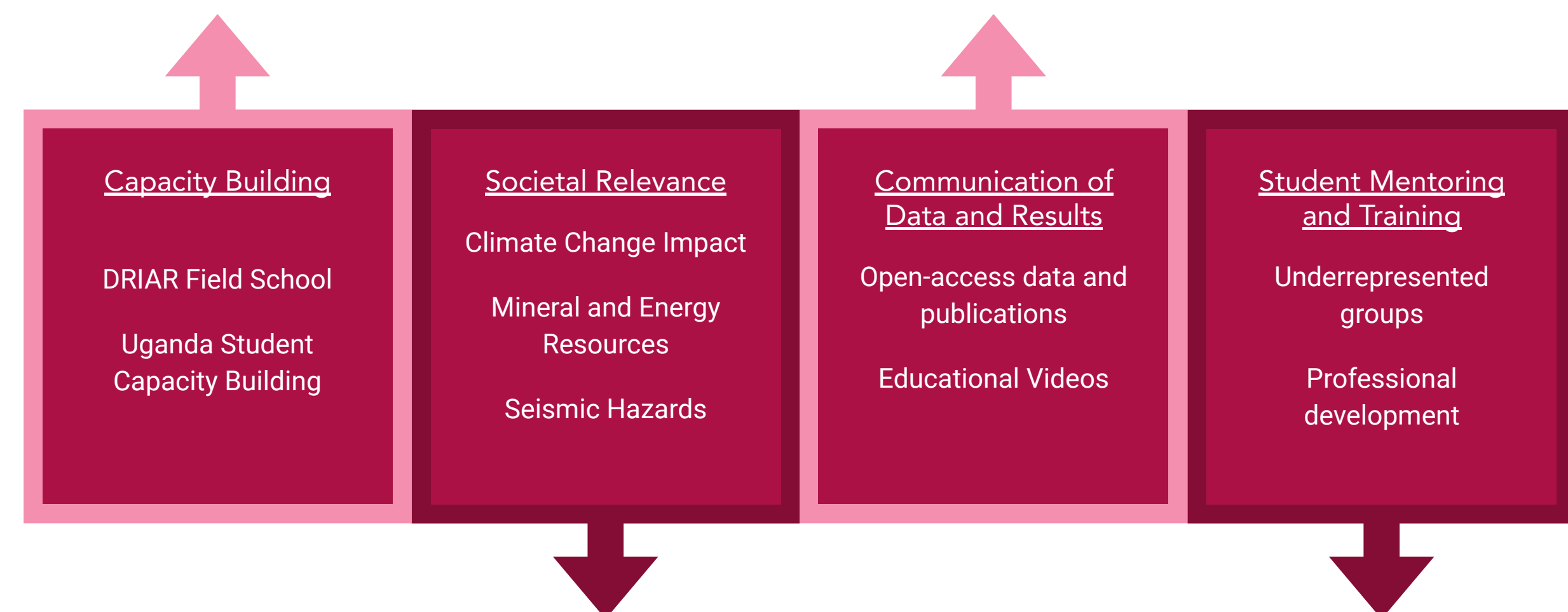


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