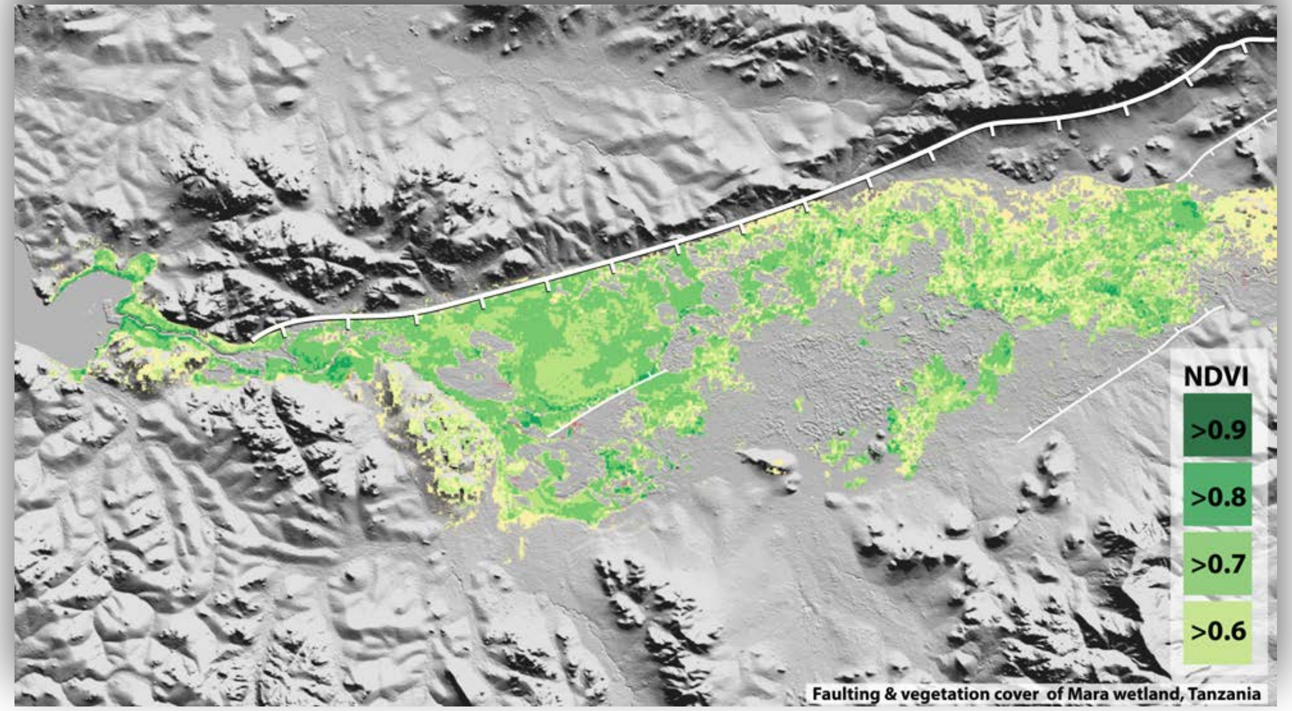
# GEOHAZARDS AND ECOSYSTEM DYNAMICS IN PROXIMITY TO ACTIVE EARTHQUAKE FAULTS - MARA RIVER BASIN, TANZANIA

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09.10.2023

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# Project Description

## 1. Starting Point

### 1.1. State of the art and preliminary work

#### 1.1.1 Motivation and scientific background

Research in active tectonics usually emphasizes the **destructive nature** and seismic hazard related to earthquake processes. We strive to broaden this perspective by considering the **ecosystem functions** of active fault structures and analyzing both the **constructive and advantageous elements** of tectonic faulting on water storage and nutrient provision, as well as the potential adverse effects on ecosystem functions, such as the **mobilization of toxic elements or nutrient leaching**. Our hypothesis posits that within tectonically active regions, fault activity plays a previously under appreciated role in regulating long-term ecosystem dynamics and human subsistence by influencing crucial factors like **soil formation, water retention, and vegetation cover.**

Tectonically active regions host some of the most diverse ecosystems on this planet. Topographic complexity in regions of active faulting results in increased environmental variability and creates regions of vastly enhanced species richness compared to adjacent regions of low relief (Badgley, 2010; Badgley et al., 2017). Striking examples are found in the South American Andes (Patterson et al., 2003), the Australian coastal mountains (Strahan, 1995) and the East African Rift System (Ring et al., 2018). Yet, understanding the range of physical and chemical processes in active fault zones and their influences on ecosystem processes has to date received relatively little attention in both geological and ecological research approaches. Understanding the value of fault activity in an ecological context is indeed puzzling as tectonic processes can be both harmful and beneficial for a variety of ecosystem functions. While destructive events like earthquakes and volcanic eruptions are major geological hazards (e.g. England and Jackson, 2011; Kadri et al., 2014; Landgraf et al., 2017), long-term faulting processes and subsequent surface deformations are important agents of landscape diversification, water resource distribution and soil formation (e.g. Bailey et al., 2011; Cuthbert and Ashley, 2014; Cuthbert et al., 2017; Dixon et al., 2012; Dosseto et al., 2011; Kübler et al., 2021; Reynolds et al., 2016; Switzer et al., 2016; Zheng et al., 2016). The influence of tectonic surface faulting on plant growth has long been used in tectono-geomorphic mapping approaches where linear vegetation zones are used as proxies for the locations of active fault traces (e.g. Kalenov, 1991; Rymer et al., 2002; Trefois et al., 2004). Subsurface fractures and subsiding basins commonly occur in fault zones and are effective means to trap water and sediments and by this control formation of climatically buffered wetlands and spring lines (Cuthbert et al., 2017; Forsberg et al., 2000; Mietton et al., 2018; Reynolds et al., 2016). On the contrary, fault zones can also contribute to segmentation of aquifers through the effect of clay smearing (Bense and Van Balen, 2004). The distinctive hydrological and pedological properties of fault-controlled landscapes can locally buffer fluctuating climatic conditions if ongoing fault motion keeps the surface close to the water table (Bailey et al., 2011; Cuthbert and

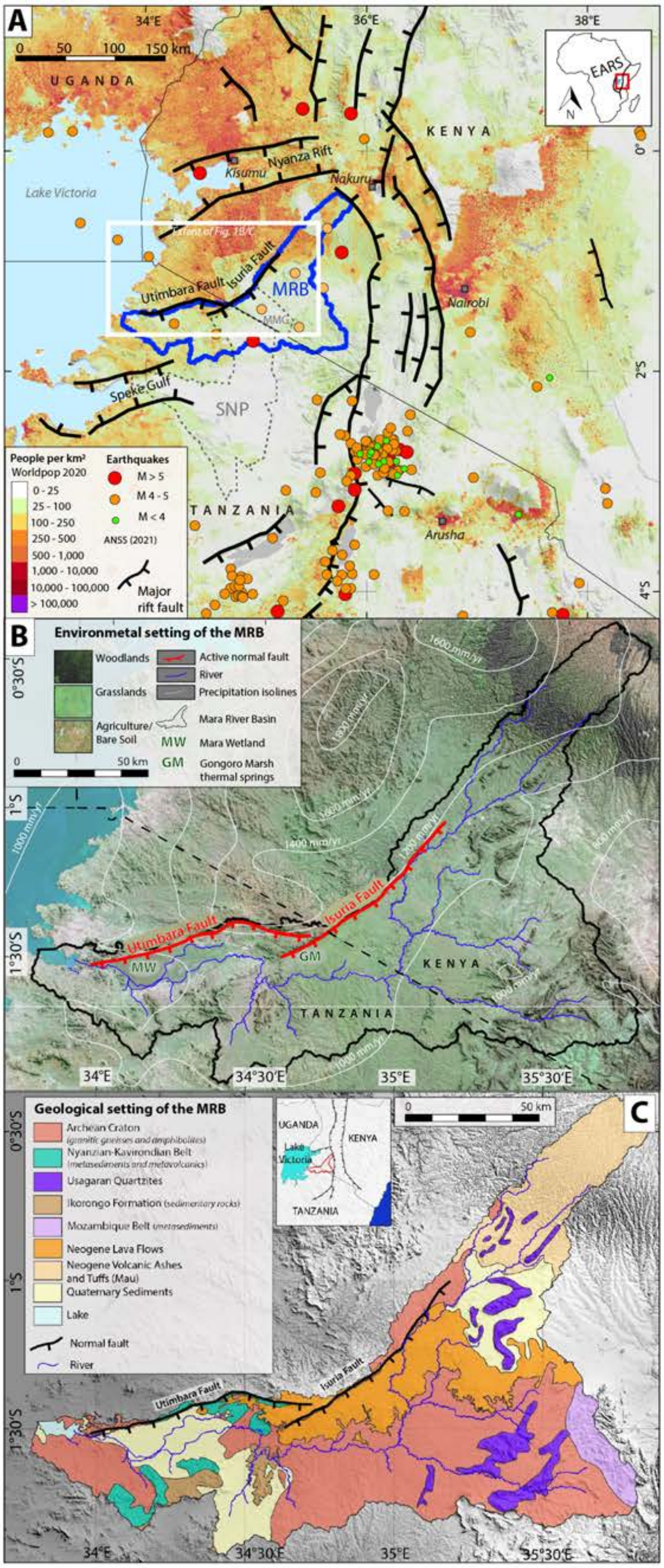


**Figure 1 | Setting of the study area (A) Seismicity and population density of the eastern branch of the EARS and Lake Victoria region; Note the proximity of the IUFZ to the densely populated Lake Victoria region, which represents one of the fastest urbanizing regions of the African continent; (B) Landuse map of the study region showing how the IUFZ acts as hydrological boundary of the Mara River basin. Precipitation isolines derived from WorldClim version 2.1 by Fick and Hijmans (2017); (C) Simplified geological map of the study area.**

Ashley, 2014; Cuthbert et al., 2017). Remote sensing and field based vegetation and soil analyses in semi-arid climates, indicate that evergreen vegetation zones along fault zones are an important contributor to the long-term storage of soil organic carbon (e.g. Hofhansl et al., 2020; Kübler et al., 2021; McCarthy et al., 1997; Mitra et al., 2005). Erosion and weathering processes along active faults lead to an immediate and - with persistent displacement activity - continuous rejuvenation of the soil and the nutrients it contains (Buendia et al., 2010; von Blanckenburg et al., 2021). While nutrient depletion through pedogenic relocation processes and deep-seated weathering predominately affect old and long exposed cratonic regions, soils in tectonically active landscapes are characterized by comparatively high nutrient levels and edaphic diversity. Also, tectonic activity promotes volcanism, and volcanic soils are often characterized by a high cation exchange capacity, a broad spectrum of soil nutrients and thus high fertility - especially if the soils contain a high content of volcanic ash and / or glass (Schiffman and Southard, 1996; Weisenberger et al., 2020; Yimer et al., 2008).

On the contrary, mobilizations of potentially harmful substances are commonly observed along fault zones. Fluoride levels in ground- and surface waters of the East African Rift System represent an enormous health hazard, particularly in the central and southern Kenya Rift, and northern Tanzania (Gaciri and Davies, 1993; Olaka et al., 2016). Release and distribution of Fluoride is directly linked to thermal springs discharging along tectonic and volcanic structures. Similar observations were made for high arsenic levels in fault zones of the southern Ethiopia rift (Rango et al., 2013) and enhanced levels of boron, zinc and nickel in tectonically controlled thermal springs of the eastern Aegean (Bencini et al., 2004; Lambrakis and Stamatis, 2008).

### 1.1.2. Setting of the study area

The focus study region of the proposed project will be the **Mara River Basin** (hereafter MRB) in the transboundary region of Tanzania and Kenya, respectively (**Fig. 1**). This region is situated between the eastern and western branches of the tectonically active East African Rift System (hereafter EARS) within the Victoria microplate (Dessu and Melesse, 2012). It represents a key region to study the connection between active tectonics, geology, ecosystems processes, and human-landscape-interactions. The basin has received much attention from both researchers and tourists due to a rich faunal diversity associated with the famous Serengeti National Park and Masai Mara Reserve. However the role of active faulting in shaping the landscape and environment of the region is not well understood. The MRB is characterized by a complex topographic and geological setting (**Fig 1 C**), and an extremely rich biodiversity comprising the famous Serengeti National Park (Tanzania) and Maasai Mara Game Reserve (Kenya) (**Fig 1 A, B**). Todate this sensitive ecosystem is severely threatened by climate change and anthropogenic processes due to strong population growth in the Lake Victoria region (Dessu and Melesse, 2012; Mango et al., 2011). An assessment of the suite of natural geological and tectonic processes influencing the stability of fertile soils and vegetation the MRB, and potential benefits and issues related to tectonically stimulated mobilization of nutrients and pollutants would be highly relevant to better understand the dynamics and threats, but also potential remedy strategies to protect this sensitive ecosystem.

In the MRB (**Fig. 1, 2**) the interplay between geological and ecosystem processes has had long-lasting impacts on human and animal subsistence starting in the Early Pleistocene (Badgley, 2010; Bailey et al., 2011; Couvreur et al., 2021; Peters et al., 2008; Ring et al., 2018). The northern part of the MRB is tectonically controlled by extensional faulting starting in the Pliocene (Macgregor, 2015; Ring, 2014; Shackleton, 1946), and leading to formation of a complex landscape and a great diversity of plant and animal species (Jager, 1982; Peters et al., 2008; Sinclair and Norton-Griffiths, 1995). The ***Isuria-Utimbara Fault Zone*** (hereafter IUFZ) represents a major tectonic structure of the region (**Fig. 1, 2 A**) controlling the hydrological development of the Mara river catchment as well as the distribution of agricultural and urban areas (**Fig. 1 A, B**). The IUFZ is located within the Tanzanian craton in the interior of the Victoria microplate (e.g. Glerum et al., 2020) and is one of a series of graben systems (**Fig. 1 A**) striking obliquely to the main rift centers of the East African Rift System (EARS). Due to a lack of seismic stations and paleoseismological studies, the activity and kinematics of the IUFZ are practically unknown. Deciphering the driving mechanisms of intraplate faulting in this complex setting would provide novel insights into the deformation history of the Victoria microplate as well as the opening mechanisms of the EARS (Glerum et al., 2020; Saria et al., 2014). The IUFZ, similar to the Nyanza rift to the north and Speke Gulf to the south (Fig. 1a), has previously been interpreted to represent a "failed" rift

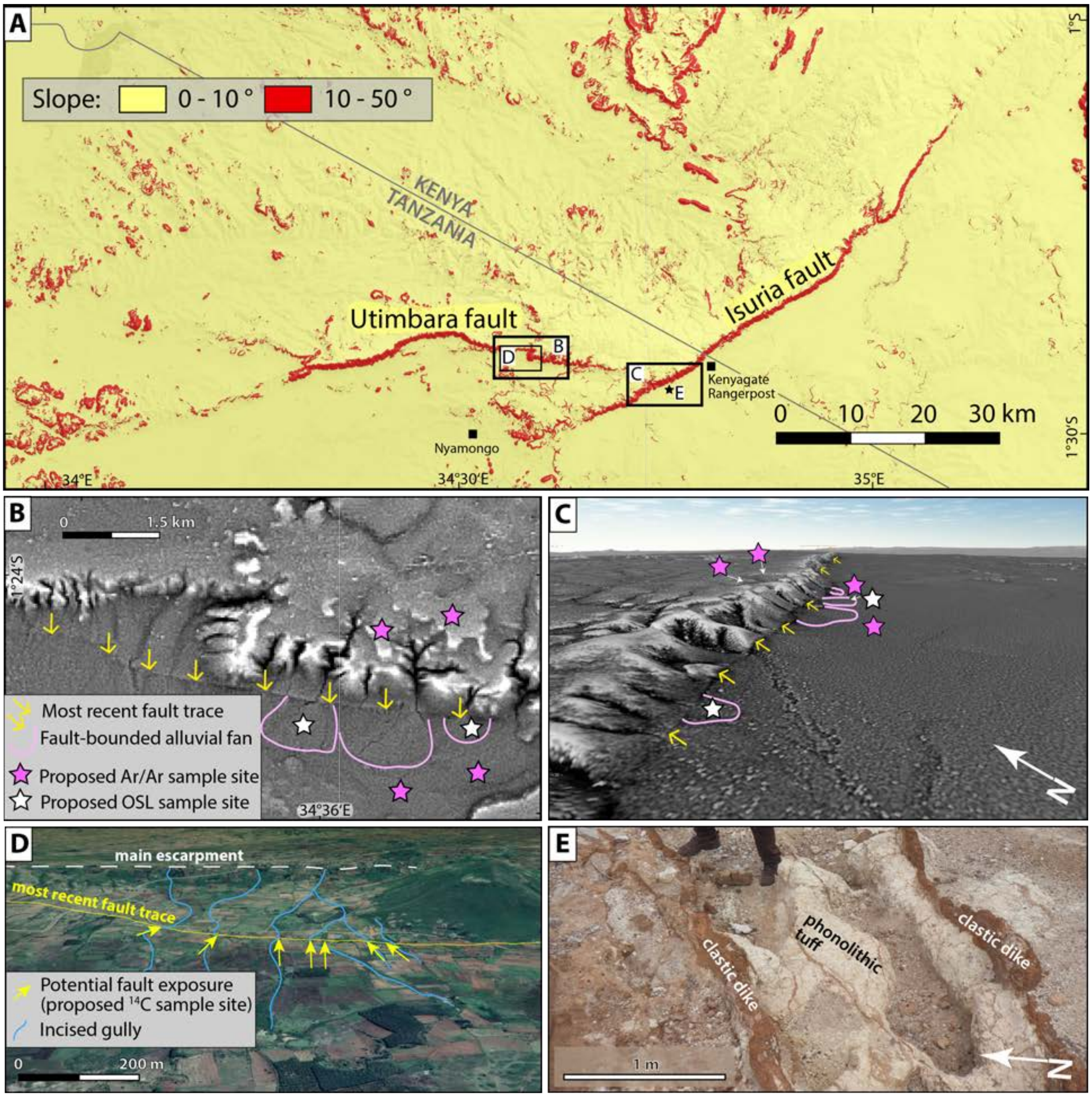


**Figure 2 | Geomorphic indicators for sub-recent surface faulting in the MRB; (A) Slope map of the study area, derived from 12 m TanDEM-X data (global DEM), fault escarpments of the IUFZ and other structural features show up as red linear structures defined by regions of steep slopes; (B) Texture-shaded image of the Utimbara fault showing a clear E-W trending fault scarp south of the main escarmpment. Small alluvial fans originate downslope of fault scarp, thus OSL dating could bracket fan formation as proxy for Pleisto-Holocene fault activity along IUFZ; (C) Texture-shaded image showing most recent fault scarp and fault-bounded alluvial fans along the Isuria fault; (D) Google Earth image of the Utimbara fault displaying potential fault exposures along fluvial incisions cross-cutting the most recent fault scarp; (E) Outcrop of a complex extensional fault zone in a tributary of the Mara river south of the main Isuria escarpment exposing sub-vertical clastic dikes and zones of iron and clay enrichment (red-brown) disrupting neogene phonolithic tuff deposits; orientation of dikes is subparallel to the main strand of the Isuria fault suggesting a coseismic origin of the dike features resulting from tectonic activity along the IUFZ location indicated in (A).**

arm and tectonically inactive since the late Neogene (Burke and Dewey, 1973; Shackleton, 1946). In general, fault systems in the Lake Victoria region located outside the EARS (**Fig 1 A**) are poorly studied and thus far, no recently active fault in this region has been identified. However, these structures pose a potentially underestimated seismic hazard, because large earthquakes in such settings can have very long recurrence intervals of $10^3$-$10^5$ years (e.g. Landgraf et al., 2017; Calais et al., 2016). A large earthquake affecting the Lake Victoria region would be extremely devastating as it is one of Africa's fastest urbanizing regions (Güneralp et al., 2017).

Seismic catalogues indicate recent seismic activity in the hangingwall of the the IUFZ and at least three events of moment magnitude ($M_W$) > 4 (**Fig. 1 A**) in the last 20 years (USGS, 2021). This suggests that the seismic activity of the IUFZ has previously been underestimated. Conservative estimates of potential maximum magnitudes of the fault zone, based on maximum surface rupture length (**Fig 2 A-C**) and surface offset (Ludat & Kübler, *submitted*), range from $M_W$ 6.5-7.5 (Wells and Coppersmith, 1994). Improved knowledge on the timing and magnitudes of past earthquakes along the IUFZ would have major implications for the seismic hazard assessment of the MRB as well as the entire Lake Victoria region.

The IUFZ represents the northwestern topographic boundary of the Serengeti-Mara ecosystem, a region world famous for its unique biodiversity and species richness (Oindo et al., 2003; Sinclair and Norton-Griffiths, 1995). In the last decades, the role of climatic and biological processes controlling ecosystem dynamics - particularly the large scale seasonal animal migrations - have been intensively studied in this region (Jager, 1982; Li et al., 2020; Peters et al., 2008). However, geological and particularly tectonic activity as drivers and stabilizers of vegetation growth, soil nutrient release and faunal migration dynamics have so far not been considered. The Serengeti-Mara ecosystem is located in a climatically sensitive region prone to be strongly affected by climatic fluctuations in the future (Ritchie, 2008). Additionally, the region is severely under stress from anthropogenic forces (e.g. Green et al., 2019).

The ecological impact of the IUFZ is expressed by several fault-controlled hydrological anomalies and seasonally stable vegetation features. The largest of which is the Mara wetland covering an area of ca. 550 km² near the mouth of the Mara River (Fig. 2a). The wetland is up to 25 m deep and directly tied to the hydrology of Lake Victoria (Dutton et al., 2019). Wetland subsidence is controlled by the activity of the Utimbara fault, located to the north and partly buried underneath the wetland (Bregoli et al., 2019; Kabete et al., 2012).

### 1.1.3. Preliminary work as prerequisites of the proposed project

Preliminary geospatial mapping of the IUFZ reveals clear geomorphic indicators **of sub-recent surface rupturing activity** of a previously undocumented seismic structure in the interior of the Victoria microplate. The observed tectonic features are among the most continuous and best preserved examples of neotectonic surface faulting in Eastern Africa.

Preliminary remote sensing analysis of vegetation and soil dynamics in the MRB illustrates a **systematic correlation between active faulting, hydrology and vegetation**, in a region of high seasonal precipitation variablility.

The Principal Investigator (PI) Simon Kübler (SK) has well-established expertise in earthquake geology and paleoseismology (Kübler et al., 2017, 2018; Landgraf et al., 2017; Gold et al., 2017; Stein et al., 2017). He has been involved in a pilot project between 2013 and 2017 (ERC advanced grant DISPERSE, awarded to Geoffrey Bailey and Geoffrey King) that focused on the interplay between geological, tectonic and soil nutritional processes in the East African Rift and their impact on Pleistocene animal migrations and early hominin subsistence (Devés et al., 2015; Kübler et al., 2015, 2016, 2019, 2020, 2021). This approach provided new insights into the role of tectonic landscapes in soil and ecosystem dynamics. It also made clear that a combination of modern satellite remote sensing techniques and field based geo-pedological (i.e. systematic mapping and analysis of rock and soil types) campaigns is most promising in disentangling the complex interactions between geological, climatic and anthropogenic processes. Preliminary work in the Serengeti-Mara region included satellite remote sensing and geospatial analysis, which resulted in a Master's thesis at the Faculty of Geosciences, LMU Munich (Ludat, 2022), as well as in a peer-review article published in *Biogeosciences* (Ludat and Kübler, 2023). Preliminary field observations were made during a 10-days reconnaissance field survey (Eckmeier et al., 2020) in the Serengeti-Mara region in October 2019, funded by the LMU Munich, faculty of geosciences, (Innovationsfond@GEO, awarded to Eileen Eckmeier and Simon Kübler).

*Preliminary assessment of fault activity in the Mara River Basin*

First results of remote sensing mapping show compelling geomorphic indicators of repeated Quaternary-to-recent coseismic surface faulting in the MRB. Preliminary mapping of aerial photos and digital elevation models indicate extensional and transtensional fault activity along the IUFZ (**Fig. 2**). Fault activity postdates a series of approximately 3.5 Ma old phonolitic lava deposits (**Fig 1 C**) (Shackleton, 1946) vertically displaced by up to 400 m and typical half-moon shaped displacement patterns for the individual fault segments. The latest surface faulting activity affects Pleisto-Holocene colluvial and alluvial deposits visible on optical satellite imagery (ESRI world imagery and Sentinel 2) as well as TanDEM-X global DEM data (12 m horizontal resolution). A series of aligned and well-preserved fault scarps exposed in unconsolidated colluvial deposits likely resulting from one or several (sub)-recent earthquakes could be traced over a distance of ~45 km along the Utimbara segment, and ~25 km along the Isuria segment, respectively, of the IUFZ (**Fig. 2 B, C**). Scarp heights vary from 4-15 m and faults show indications of horizontal fault motion through laterally offset drainages crossing the surface scarps (**Fig. 2 D**). Preliminary field data suggest distributed hangingwall deformation patterns illustrated by a series of clastic dikes and small-scale normal faulting exposed in river channels south of the main Isuria escarpment (**Fig. 2 E**). Additional geomorphic features supporting the hypothesis of sub-recent fault activity are a series of small (0.1-0.5 $km^2$), half-moon shaped alluvial fans, depositing directly underneath the surface scarps along several segments of the IUFZ (**Fig. 2 B, C**). Geochronological data on displaced volcanic rocks, as well as sedimentary layers and alluvial surfaces would provide crucial information on the Neogene-to-recent surface faulting activity along the IUFZ and on space-time patterns of tectonic activity within the Victoria microplate.

*Geo-ecosystem interactions in the MRB*

The long-term fluvial development of the MRB is strongly influenced by the fault structures and tectonic evolution of the EARS and IUFZ. The westward flow and onset of fluvial network development in uppermost catchment of the Mara river is controlled by the uplift and back-tilting of the Mau Escarpment in Central Kenya, West of Nakuru (**Fig. 1 A**). Also, the asymmetry of the MRB results from the IUFZ acting as topographic barrier and northern boundary of the river catchment (Figs. 1 B, 2 A).

Green vegetation zones visible on optical and multispectral satellite data are associated with fluvial and topographic features of the Mara River, and IUFZ, respectively. Preliminary analysis of spectral indices highlighting vegetation, soil moisture and pedogenic clay (**Fig. 3**) suggests that regions of seasonally stable vegetation and soil conditions are associated with the active fault structures of the IUFZ. The Normalized Difference Vegetation Index (NDVI) (**Fig. 3 A**) highlights several locations with persistently high values indicating healthy vegetation which are likely connected to tectonic and/or hydrological processes. The Mara Wetland (**Fig. 3 B**) downslope of the Utimbara Escarpment is a product of tectonic subsidence and northward down-warping of the hanging wall, as well as uplift and northward tilting of the footwall. Additionally, it is likely that secondary faults in the hanging wall combined with high rates of sedimentation and lake level fluctuations of Lake Victoria lead to high water retentivity and reliable water availability during dry seasons. Several smaller wetlands can be found along the Isuria fault exposing higher NDVI-values than the surrounding area. One of them – the Gongoro Marsh south of the Isuria fault– is not only fed by perennial streams but evolved around the Majimoto spring (**Fig. 3 B**) - a hot spring presumably related to geothermal activity along the Isuria fault. The area around the hot spring also appears as a location promoting clay formation and/or accumulation, as seen by enhanced mean clay mineral ratio (CMR) values (**Fig. 3 C**). The association of the fault with this hot spring provides additional evidence of sub-recent faulting activity. Colluvial sediments downslope of the main fault escarpments of both the Isuria and Utimbara fault are clearly visible as regions of stable vegetation, soil moisture (**Fig. 3 D**) and high clay content. While dynamics in vegetation cover and soil moisture are likely linked to and result from enhanced water availability within the fault zone and along tectonically subsided regions (**Fig. 4**), the enhanced clay content is more puzzling. We hypothesize that clay accumulation in fault zones is a combined effect of weathering processes and downslope transport of weatherable minerals together with fluid transport and mechanical deformation processes within the fault zone (**Fig. 4**). This hypothesis needs to b tested in systematic sampling campaigns of the soil-rock interface across fault transects in the study region (see **chapter 2.3**, **WP 5**)

## 2. Objectives and work program

### 2.1. Anticipated total duration of the project

**3 years (02/2024 - 01/2027)**

### 2.2. Objectives

The overarching goal is to decipher the <u>tectonic faulting </u>history related of the IUFZ, as well as the potential suite of <u>recent ecosystem functions controlled by fault processes</u> in the MRB and adjacent regions. Combining methods from geology, geomorphology, soil science and remote sensing we propose a multidisciplinary study to identify tectonically active structures in the MRB, and investigate the interplay between tectonic faulting and ecosystem dynamics to obtain novel insights into the role of geological processes on long-term human and animal subsistence in dynamic landscapes. Potential implications of this project are two-fold:

(A) **Studying the activity and slip history of fault structures in the MRB** will provide a first comprehensive dataset on tectonic surface deformation within the Victoria microplate; this will improve our general understanding of intracratonic fault systems, as well as the seismic hazard assessments for the densely populated MRB and Lake Victoria regions;

(B) **Analyzing the impact of active faulting on present- day soil quality, water availability and and vegetation growth** will provide novel insights into the topic of geo-ecosystem dynamics and human-landscape interactions in climatically sensitive regions. Outcomes of this study will provide a first dataset on the interplay between active faults, soils and vegetation and by this, improve our general understanding of the importance of geotectonic processes on ecosystem functions in climatically sensitive settings. More precisely, we propose to address the following objectives:

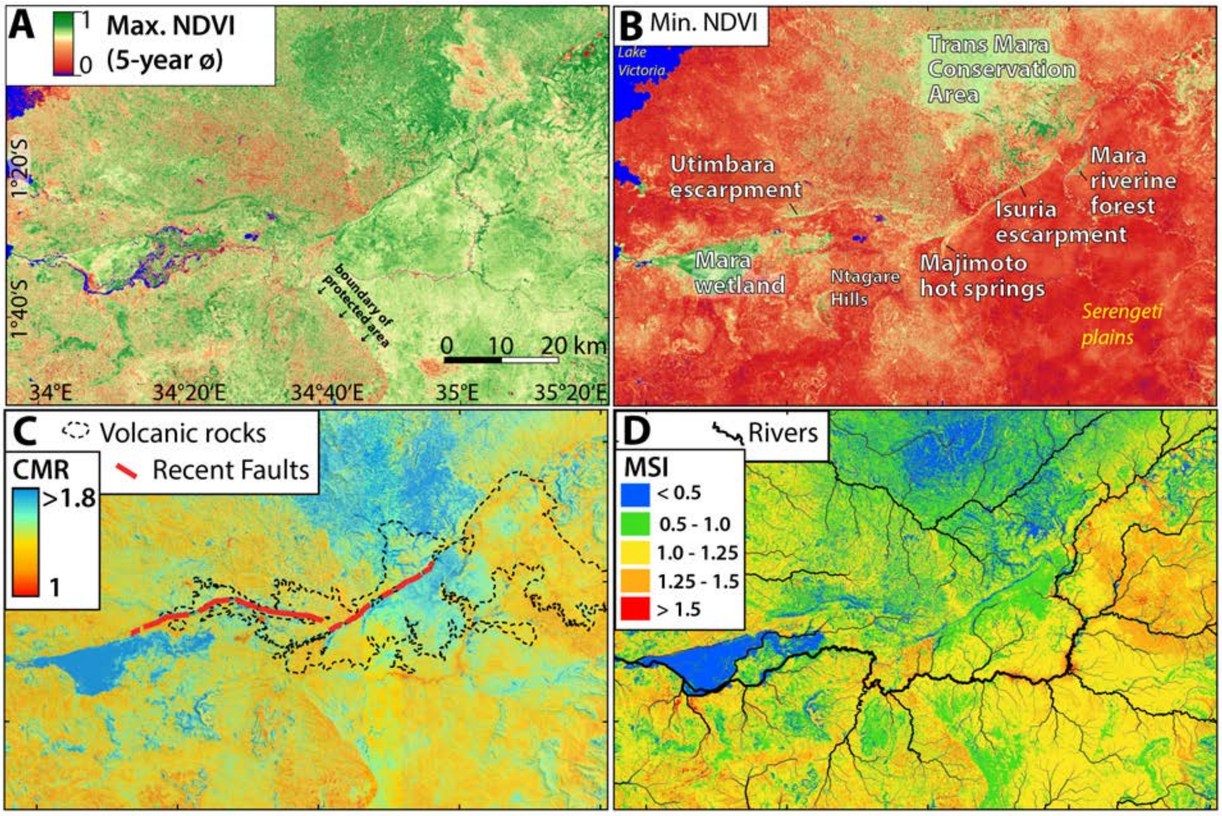


**Figure 3 | Ecosystem processes in the tectonically controlled Mara River Basin illustrated by spectral indices along Isuria and Utimbara faults calculated from 34 Sentinel-2 multispectral images from European Space Agency (ESA) acquired between 2016 and 2022. (a) Mean maximum normalised difference vegetation index (NDVI); note the strong contrast in NDVI between agricultural (West) and protected areas (East); (B) Mean minimum NDVI, locations with perennial stable vegetation are labeled in white. (b) Mean clay mineral ratio (CMR); volcanic rocks and recent fault scarps are indicated (c) Mean moisture stress index (MSI); river network is indicated.**

**Objective 1 | Tectonic activity and Pleistocene fault deformation rates |** The objective is to decipher the onset of faulting along the IUFZ and whether the surface scarps and displaced geomorphological features in the MRB identified in preliminary digital mapping approaches (**Fig. 2**) are the result of one or more surface rupturing earthquakes. We aim to acquire detailed data on the locations, extents and ages of fault structures and tectonically controlled landforms (**WP 1, 2, 3**) to better understand the sub-recent tectonic history of the MRB with important implications for understanding the internal deformation of the Victoria microplate. Information on Neogene-to-recent fault slip rates will allow a first assessment of the seismic hazard potential of the IUFZ and the fast urbanizing Lake Victoria region.

**Objective 2 | Seasonal-to-decadal hydrological and vegetation dynamics in a tectonically controlled ecosystem |** The objective is to analyze in detail how zones of seasonally stable vegetation cover and hydrological anomalies such as wetlands and natural springs in the MRB are connected to and controlled by tectonic processes. We aim to understand the role of fault zones and tectonic deformation in water storage and recharge of aquifers, and the influence on the seasonal-to-decadal dynamics of vegetation cover and soil moisture (**WP 4, 5**) in climatically sensitive regions.

**Objective 3 | Tectonic controls on soil development and critical zone processes in the Mara River Basin |** The objective is to decipher how active surface faulting affects soil development and the status of the "Critical Zone" - the permeable layer between the top of the vegetation cover and the groundwater basis - in the MRB, with emphasis on (a) weathering and element mobilization processes at the soil-rock interface, particularly in "faulted vs. unfaulted" settings; (b) fluvial processes leading to sediment (re-)distribution of sediments from different source areas and its effect on soil nutrient availability and soil-rejuvenation; (c) terrain effects such as slope steepness and altitude on soil nutrient variability in a topographically complex landscape. Main tasks include systematic remote sensing and field mapping and sampling (**WP 4, 5**) as well as "real-time" and "in-lab" chemical analysis of rocks and soils along cross-fault transects to obtain a detailed geopedological dataset of the MRB (**WP 5, 6**).

### 2.3. Work program including proposed research methods

***Work Package (WP)1 | Tectonic analysis - Remote sensing and GIS | Apr 2024 - Sep 2024 |*** During the first six months the doctoral student (NN) will familiarize with the research topic (literature, methods, data review) and compile a comprehensive digital geotectonic database of the study region. SK will supervise NN and a student helper (HW) will support data compilation from existing literature and online databases. Additional geological, structural and geomorphological information of the MRB and IUFZ will be derived from integrated remote sensing, geospatial and GIS-based mapping approaches, carried out by NN and supported by HW. Existing gaps in geological datasets (e.g. in the Mara triangle, S-Kenya) will be filled using information from optical and multispectral satellite data (Aster, Sentinel). Preliminary fault maps that will serve as base maps for field work (**WP2**, **WP3**) will be compiled from geological datasets, seismicity catalogues and detailed studies of high-resolution topographic (TanDEM-X, Copernicus, WorldView stereo) and optical (Sentinel 2, WorldView 2/3) satellite data. Free access to commercial WorldView datasets will be granted through collaboration with Dr. Ryan Gold (USGS, Golden, USA, see attached letter of support).

***WP 2 | Tectonic analysis - Field mapping | Sept 2024 - Oct 2024 |*** During a 4-week-long field campaign to the MRB in northern Tanzania, carried out by SK and NN, the surface expression and timing of sub-recent earthquakes along the IUFZ will be determined using geomorphological and geological field methods. After collection of all necessary permits (see section 5.1.2.2.) , field sites will be selected based on the geomorphic expression and continuity of tectonic features (**Fig. 2 B, C**), as well as their relevance in relation to the tectonic and ecological research objectives (**WP 3**, **WP5**), respectively. To obtain quantitative data on the timing of fault motion (**WP3**) and magnitude of coseismic events, natural and artificial fault exposures (river incisions, bedrock fault scarps, road cuts, quarries, etc.) will be analyzed. To determine the maximum age of fault activity along the IUFZ (**WP3**), rock samples from the displaced phonilitic unit will be collected, which crops out at the top of the escarpments and at the base of the Isuria fault's footwall (**Fig 1 C).** Fault scarp heights and fault displacements (if exposed) will be measured and radiocarbon samples, as well as OSL samples from quartz and feldspar-bearing, displaced sedimentary layers will be collected. The tectonic influence on formation of several alluvial fans along the IUFZ (**Fig 2 B, C**) will be analyzed by field mapping. Sampling of alluvial sediments for OSL analysis (**WP3**) will be collected in sampling pits on alluvial fan surfaces downslope of active fault structures to receive age information on fan formation as proxy for past faulting activity. Proposed sampling locations along the Utimbara fault are in vicinity of Nyamongo village (**Fig. 2 A**) with good road access to potential fault exposures and alluvial deposits. Proposed sampling along the Isuria fault are on the alluvial fan directly north and SW of Kenyagate Rangerpost (**Fig. 2 A**), at the NE gate of Serengeti National Park.

***WP 3 | Fault rupture patterns and seismic hazard assessment | Nov 2024 - May 2025 |*** To bracket the Cenozoic onset of faulting along the IUFZ, $^{40}$Argon/$^{39}$Argon (Ar/Ar) dating (collaboration with Florian Hofmann, University of Fairbanks) of tectonically displaced Neogene phonolites in the vicinity of the IUFZ will be performed. By analyzing a total of four phonolitic rock samples from both the hanging wall and footwall of the fault, and comparing their ages, one can identify the maximum age of Neogene fault activity as well as any age offset due to fault motion. Proper care must be taken during sampling to ensure that the phonolites have not experienced significant post-emplacement argon loss, through e.g. magmatic or hydrothermal activity, which could otherwise compromise the accuracy of the dating results. To determine absolute ages of sediment deposition and by this bracket the timing of Pleistocene-to-recent faulting events, radiocarbon and OSL samples from earthquake event layers and fault controlled sedimentary deposits (**WP2**) will be processed and analyzed. Radiocarbon dating will be performed at the Gliwice Absolute Dating Method Centre (Gliwice, Poland). OSL dating will be performed at the OSL labs at the Curt-Engelhorn-Centre of Archeometry (CEZA) in Mannheim. Results on age dating will be implemented in field results on fault mapping. Using empirical relationships of fault parameters (e.g. surface rupture length, surface displacement) and the release of seismic energy (e.g. Wells and Coppersmith, 1994; Leonard, 2010), maximum earthquake magnitudes will be determined.

Concurrently, by evaluating time-space rupture patterns, the propensity of the studied fault zone for earthquake clustering versus isolated "one-shot" seismic occurrences will be ascertained to achieve a comprehensive understanding of the long-term seismic behavior of the fault. By extrapolating past fault activity and behavior to present-day conditions the current and potential future seismic hazards posed to the densely populated Lake Victoria region will be evaluated (collaboration with Ryan Gold).

***WP 4 | Geo-pedological analysis - Remote sensing and GIS | Apr 2025 - Aug 2025 |*** Topsoil characteristics (e.g. clay content, organic carbon) as well as dynamics of vegetation vigor and soil moisture in the Mara river basin on seasonal-to-decadal time scales will be extracted from time series analysis using time-stacked multispectral (Landsat, Sentinel), and hyperspectral (EnMAP) satellite data. Processing and analysis of satellite data will be performed by NN with support by HW. In this WP, NN will also work closely with Dr. Alfred Said, a hydrogeochemist and expert in GIS-based groundwater modeling (collaboration confirmed in letter by Prof. Revocatus Machunda, Nelson Mandela African Institute of Science and Technology (NM-AIST)). Dr. Said will lend his expertise in identifying regions of interest for groundwater sampling and pinpointing areas with intensive land cover dynamics to enhance the planning of the field campaign, (WP5). We also collaborate with Dr. Stefanie Rieger (LMU Munich), who is an expert in geological remote sensing and processing of multi- and hyperspectral satellite data. EnMAP data will be acquired under the ongoing announcement of opportunity (AO) “A00002 Long-Term Ecosystem Monitoring”, of the German Aerospace Centre (DLR Oberpfaffenhofen). To compare results with annual-to-decadal rainfall patterns in the study regions, precipitation data of the Tropical Rainfall Measuring Mission (TRMM) will be used and complemented with detailed precipitation measurements from local meteorological surveys obtained through the collaboration partners at NM-AIST.

***WP 5 | Geo-pedological analysis - Field work | Aug 2025 - Sep 2025 |*** During a 4-week-long field campaign to the MRB in northern Tanzania, carried out by SK and NN, geo-pedological (geological and soil field mapping) approaches will be performed, with the aim to connect the geochemical signatures of the geological substrate (bedrock, sediment) with soil chemical and vegetation characteristics along topographic transects across the active fault strands of the IUFZ. Remote sensing analysis (**WP4**) will be complemented by high-resolution local-scale analysis of vegetation growth and soil moisture across several sampling transects. Systematic rock and soil sampling will be carried out along <u>lithosequences</u> (soil development on different rock/sediment types in comparable topographic and climatic settings) and <u>toposequences</u> (soil development along topographic profiles within the same lithological unit). Three sampling transects will crosscut the active fault strands of the IUFZ (identified in **WP1**, **WP2**). Two further transects will crosscut other, tectonically inactive topographic features in the Mara River basin such as river terraces and precambrian fold structures. To obtain maximum data density and sample spacings of a few 10s of meters to capture local-scale variability of soil characteristics, NN will analyze the chemical characteristics (levels of main oxides and trace elements) of the majority of rock and soil samples directly in the field using a portable X-Ray Fluorensence (pXRF) analyzer. The pXRF will be provided by the Department for Cultural studies and Antiquity at LMU Munich, facilitated through our collaboration with Michaela Schauer (see attached collaboration letter). This way, we intend to achieve sampling numbers of 50-70 soil measurements per transect and 15-20 rock measurements per transect. Additionally, water sampling as well as sampling of spring precipitates and soils will be sampled in vicinity of the Majimoto hot spring and Mara wetland (Fig. 3 b). Water samples will be analyzed at the hydrological labs of NM-AIST, targeting potentially toxic elements including fluoride or arsenic (collaborations with Prof. Machunda and Dr. Said).

***WP 6 | Rock and soil laboratory analysis | Oct 2025 - May 2026 |*** Field data from soil mapping and pXRF analysis will beTo calibrate the field XRF data, we will in addition take a small number of rock and soil samples (3-5 per sampling transect), and ship them for further analysis at LMU Munich (collaboration with Donjá Aßbichler). Thin section of rock samples will be prepared and analyzed using cross-polarized microscopy at. Rock and soil sample preparation (glas beads for determination of major and minor elements, powder pills for trace elements) will be performed, and XRF analysis will be carried out at LMU Munich geochemical laboratories.

**WP 7 | Data interpretation and writing of publications |** Under supervision of SK, and support by the project group and collaboration partners, NN will draft publishable manuscripts on the following topics:
A: *Tectonic geomorphology and assessment of fault activity along the IUFZ.* Input data for the manuscript will be field observations combined with remote sensing and geospatial studies of the IUFZ.
B: *Soil-Rock interactions in fault zones and tectonically active settings.* Input data will be pedo-geological field data and results of chemical soil analysis and chemical as well as microscopical analysis of rock samples.
C: *Seasonal-to-decadal vegetation dynamics in tectonic landscapes.* Input data will be derived from spectral analysis of satellite time-series datasets combined with field data on soil moisture and vegetation growth.

***WP 8 | International conferences |*** The attendance of national and international meetings and conferences is important to enhance visibility of the project and allow knowledge exchange with experts. SK will introduce NN during these meetings to the scientific community on these meeting, which is highly important for NN's scientific career to build up early a large scientific network. Over the course of the project, three international conferences will be attended. In April 2024 and 2026, we will attend the European Geoscience Union Annual Meeting in Vienna, in October 2025 we will attend the Geological Society of America Annual Meeting in San Antonio (TX), USA.

***WP 9 | Finalizing and defending dissertation | Dec 2026 - Mar 2027***
The PhD student compiles the chapters and writes the synthesis of the doctoral thesis. It is recommended that NN compiles a cumulative dissertation with at least one paper published, one accepted and one ready for submission when handing in the dissertation at the University of Munich. At the earliest 6 weeks after submission, the doctoral defense can take place.

**Table 1** | Overview of time schedule, work packages and objectives of the project.

| Work packages (WP) | | Year 1 Apr. 2024 - Mar. 2025 | | | | | | | | | | | | Year 2 Apr. 2025 - Mar. 2026 | | | | | | | | | | | | Year 3 Apr. 2026 - Mar. 2027 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WP | Content | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 |
| 1 | Tectonic analysis - Remote sensing & GIS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | Tectonic analysis - Field work | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Geochronology of fault activity | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | Geo-pedological analysis - Remote | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | Geo-pedological analysis - Field work | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Rock & soil analysis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | Data interpretation & Publication | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | International conferences | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | Writing & thesis defense | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

| Key to colors | | GOAL | |
|---|---|---|---|
| | | Identification of active faults and fault-controlled ecosystem functions in the Mara River Basin (Northern Tanzania) | |
| NN | Doctoral Student | OBJECTIVES | |
| SK | Simon Kübler | OBJ 1 | Tectonic activity and fault deformation rates |
| HW | Student assistant (HiWi) | OBJ 2 | Tectonic controls on soil development/critical zone processes |
| | | OBJ 3 | Seasonal-to-decadal hydrological and vegetation dynamics |

## 2.4. Handling of research data

Geological samples will be stored in the rock archive of LMU Munich, Geology. Soil samples will be stored at the soil labs of NM-AIST. Analysis results and other raw data will be shared with team members and collaboration partners, following the rules of good scientific practice. Publication of data will be done via international peer-reviewed and preferably open access publications. Raw data will be published along with results in peer-review journals as soon as possible. Data and findings will be also presented at national and international workshops and conferences. Topographic data will be made accessible via the OpenTopography network, in-line with legal requirements related to individual datasets. Large ecological and environmental datasets will be published via PANGAEA or similar data publishing services.

## 2.5. Relevance of sex, gender and/or diversity

Sex, gender, and/or diversity are irrelevant to the project. However, at LMU Geology, we stand for a gender-balanced and diverse working environment, and we also aim at enhancing the number of female scientists and people from a diverse background in research projects. The selection process for the PhD position will therefore assure a selection of at least 50% of potential female candidates. The student assistant part in the project will be given to a student with equal opportunity for everyone despite their sex, gender, and/or ethnicity. As part of the project's overarching strategy, we will actively foster collaboration with international colleagues, with a particular emphasis on engaging institutions from the Global South. This concerted effort is aimed at enriching the project's diversity and global perspective.

# 3. Project- and subject-related list of publications

Badgley, C., 2010, Tectonics, topography, and mammalian diversity: Ecography, v. 33, no. 2, p. 220-231, DOI: https://doi.org/10.1111/j.1600-0587.2010.06282.x.
Badgley, C., Smiley, T. M., Terry, R., Davis, E. B., DeSantis, L. R., Fox, D. L., Hopkins, S. S., Jezkova, T., Matocq, M. D., and Matzke, N., 2017, Biodiversity and topographic complexity: modern and geohistorical perspectives: Trends in Ecology & Evolution, v. 32, no. 3, p. 211-226, DOI: https://doi.org/10.1016/j.tree.2016.12.010.
Bailey, G. N., Reynolds, S. C., and King, G. C., 2011, Landscapes of human evolution: models and methods of tectonic geomorphology and the reconstruction of hominin landscapes: Journal of human evolution, v. 60, no. 3, p. 257-280, DOI: https://doi.org/10.1016/j.jhevol.2010.01.004.
Bencini, A., Duchi, V., Casatello, A., Kolios, N., Fytikas, M., and Sbaragli, L., 2004, Geochemical study of fluids on Lesbos island, Greece: Geothermics, v. 33, no. 5, p. 637-654, DOI: https://doi.org/10.1016/j.geothermics.2003.11.003.
Bense, V. F., & Van Balen, R. (2004). The effect of fault relay and clay smearing on groundwater flow patterns in the Lower Rhine Embayment. *Basin Research*, *16*(3), 397-411.
Bregoli, F., Crosato, A., Paron, P., and McClain, M., 2019, Humans reshape wetlands: Unveiling the last 100 years of morphological changes of the Mara Wetland, Tanzania: Science of the Total Environment, v. 691, p. 896-907, DOI: https://doi.org/10.1016/j.scitotenv.2019.07.189.

**Working hypothesis:**

In the Mara River Basin, active surface faulting exerts a strong control, not only on landscape evolution and surface deformation dynamics, but also on the **seasonal-to-decadal stability of vegetation** and **availability of (near-) surface water**, as well as on the **quality and nutrient status of soils**.

This hypothesis will be tested by monitoring variations in soil, water and vegetation parameters across both active fault structures and tectonically quiescent surface features. Further tests will focus on basin-wide analysis of seasonal-to-decadal ecosystem dynamics.

Investigations will include i) tectonogeomorphic field mapping and age determination of past surface faulting events, ii) field and lab-based analyses of rock and soil physicochemical properties, and iii) remote sensing time-series analysis of vegetation growth and soil formation.

Outcomes of the project will allow constraining i) the most recent surface faulting activity and associated seismic hazard in the Mara River Basin and surrounding regions, ii) the interrelations between tectonic, pedological and ecological processes, and iii) the long term dynamics and localized stability of vegetation growth and soil productivity patterns in a geologically complex and climatically sensitive ecosystem.

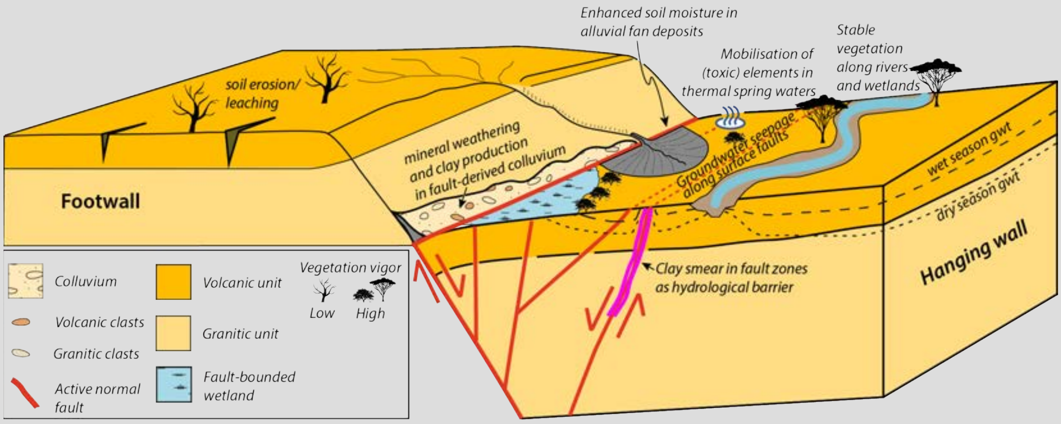


**Figure 4 | Conceptual 3D model of a tectonically controlled ecosystem, resembling the range of geological and ecological features found in the study area, as well as the hypothesized hydrological, pedological and vegetation dynamics influenced by the presence and repeated activity of active normal faulting. Proposed geo-pedological sampling aims to capture physicochemical and nutritional variations over cross-fault transects from the uplifted footwall across the fault zone and into the subsided hanging wall, as well as soil and water variability in vicinity of specific hydrological features such as thermal springs and wetlands.**

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## 4. Supplementary information on the research context

### 4.1. Ethical and/or legal aspects of the project

#### 4.1.1 General ethical aspects

Data acquisition for the project will rely on field work, as well as sampling of geological (rocks, sediments) and pedological (soil, vegetation) samples in developing regions of northern Tanzania. During field work we will collaborate with local authorities, scientists and technicians from local universities and research facilities as well as smallholder farmers, livestock herders and village residents. Employed field staff will be a mixture of English speaking and non-English speaking participants. Field work will involve sampling (rocks, soils, plants), soil pit excavation as well as outcrop mapping on private farmland, public land, and in conservation areas.

To avoid communication problems during field work, which would potentially increase vulnerability of local residents, we will employ local field guides who will be able to speak English, Swahili, and the local tribal languages of the corresponding field localities. If invasive exploration methods (excavation of soil pits), will be carried out on farmland and other types of private land, we will compensate farmers and landowners according to locally appropriate rates. All employed staff will be officially hired through local universities and research institutes. Access to conservation areas will be granted through research permits of the research commissions and wildlife services in the corresponding countries. I have been granted research permits through the Tanzanian research commission (COSTECH) and wildlife service (TAWIRI) in the past and am well familiar with the application processes.

#### 4.1.2 Descriptions of proposed investigations involving humans, human materials or identifiable data

Not applicable

#### 4.1.3 Descriptions of proposed investigations involving experiments on animals

Not applicable

#### 4.1.4 Descriptions of projects involving genetic resources (or associated traditional knowledge) from a foreign country

Not applicable

#### 4.1.5 Explanations regarding any possible safety-related aspects (“Dual Use Research of Concern; foreign trade law)

Not applicable

### 4.2. Employment status information

Kübler, Simon | Dr. habil | senior lecturer (Akademischer Oberrat auf Zeit, A14),
until Jan 17th 2027
Ludwig Maximilians University of Munich | Department of Earth and Environmental Sciences | Geology

Project PI’s expertise

**Simon Kübler** has long-term experience since 2007 in conducting tectono-geomorphic and paleoseismic field studies in Europe, the United States and Africa. Since 2013 he regularly conducts field studies in the East African Rift System, and collects and analyzes soil and rock samples from Kenya and Tanzania, from outcrops, excavation pits and drill cores. He has supervised 3 MSc theses and 12 BSc theses on field based and remote sensing studies in Kenya and Tanzania. His applied methods range from traditional geological field mapping and trenching approaches to chemical analysis of rocks and soils, as well as remote sensing analysis of topographic, multispectral and radar remote sensing data.

### 4.3. First-time proposal data

Not applicable

### 4.4. Composition of the project group (in alphabetic order)

Aßbichler, Donjá | Dr. | LMU Munich | TV-L E13 until Oct 2026
Expertise: XRF Analysis, thin section microscopy, Geochemistry of igneous rocks
Carena, Sara | Dr. habil. | LMU Munich | A14 permanent
Expertise: 3D modeling of active faults, photogrammetry
Paschert, Karin | BSc | LMU Munich | TV-L E10 75 % permanent
Expertise: soil chemistry, hydrochemistry, chemical laboratory organization
Rieger, Stephanie | Dr. | LMU Munich | TV-L E13 75 % permanent
Expertise: GIS, satellite remote sensing

### 4.5. Researchers in Germany with whom you have agreed to cooperate on this project

Prof. Eileen Eckmeier, W3 Professor geoarcheology and environmental hazards, Institute for Ecosystem Research, Kiel University. Prof. Eckmeier will collaborate on planning the soil sampling campaign, reviewing the collected soil samples and provide support regarding interpretations of soil analysis data and the soil geomorphological setting of the study area (see confirmation letter attached).
Dr. Michaela Schauer, postdoctoral researcher, University of Vienna, and visiting scientist at LMU Munich, Near Eastern Archeology. Dr. Schauer is an expert in using portable X-Ray Fluorescence (pXRF) analysis in geoarcheological and pedological studies, and will provide access and technical supervision to the pXRF devices at LMU Munich (see confirmation letter attached).

### 4.6. Researchers abroad with whom you have agreed to cooperate on this project

Dr. Revocatus Machunda, Dean of School of Environmental Science, Nelson Mandela African Institute of Science and Technology (NM-AIST), Arusha, Tanzania. Dr Machunda will provide affiliation with NM-AIST as Tanzanian collaboration partner and ensure logistical support for field transportation and in acquiring all necessary permits from national and local authorities.
Dr. Alfred Said, hydrologist, University of Dodoma, Department of Environmental Engineering and Management, Dodoma, Tanzania. Dr. Said will provide expertise in surface-groundwater interactions and will consult on planning the field campaign and selection of study sites. He will participate in the field campaigns of WP2 and WP5, respectively.
Dr. Ryan Gold, research geologist, United States Geological Survey, Golden, CO, USA. Dr. Gold will consult on planning the field campaign and selection of study sites. Drawing from his proficiency in documenting morphotectonic features from field and remote sensing based datasets, he will aid in interpreting the seismic history and associated hazards of the study region. He will further provide exclusive access to commercial satellite data (WorldView 2, 3, WorldView Stereo) via his USGS affiliation (see confirmation letter attached).

### 4.7. Researchers with whom you have collaborated scientifically within the past 3 years

| | |
|---|---|
| Geoffrey Bailey | University of York (UK) |
| Katy Barnhart | USGS Golden (USA) |
| Maud Devés | University of Paris (Frace) |
| Anke Friedrich | LMU Munich |
| Nena Galanidou | University of Crete (Greece) |
| Gorgeous Iliopolus | University of Patras (Greece) |
| Annett Junginger | University of Tübingen (Germany) |
| Geoffrey King | IPGP Paris (France) |
| Sally Reynolds | University of Bournemouth (UK) |
| Carolina Rosca | University of Tübingen (Germany) |
| Peny Tsakanikou | University of Crete (Greece) |
| Gregory Tucker | University of Boulder (USA) |

### 4.8. Project-relevant cooperation with commercial enterprises

Not applicable

### 4.9. Project-relevant participation in commercial enterprises

Not applicable

### 4.10. Scientific equipment

The necessary equipment for this project is fully available or will be requested in this proposal (see section 5.1.3). All basic equipment for GIS and remote sensing analysis and computer modeling (incl. server storage), rock preparation, microscopy (polarization and SEM) and access to LMU mineralogy rock chemistry labs will be provided by the Department of Earth and Environmental Sciences, LMU Munich.

### 4.11. Other submissions

In submitting a proposal for a research grant to the DFG, I agree to adhere to the DFG's rules of good scientific practice. I have not requested funding for this project from any other source. In the event that I submit such a request, I will inform the DFG immediately. A pilot study for this project on soil-rock interactions in the Serengeti ecosystem was financed by the faculty of geosciences at LMU Munich, awarded to Simon Kübler and Eileen Eckmeier in 2019. Outcomes of this work (Ludat et al., *submitted to Biogeosciences*) are currently under review. One Master thesis (A. Ludat), and one Bachelor thesis (F. Heigl) were also conducted within this precursory project.

**Table 2** | Summary of costs

| Simon Kübler + NN (LMU Munich) | 2024 | 2025 | 2026 | 2027 | Sum |
|---|---|---|---|---|---|
| **Staff (doctoral student + HiWi)** | €43137 | €57577 | €56303 | €13894 | **€170911** |
| **Equipment (<10,000)** | €7782 | €435 | €435 | €0 | **€8652** |
| **Travel expenses NN** | €1420 | €5057 | €2165 | €0 | **€8642** |
| **Travel expenses SK** | €5760 | €3572 | €2560 | €0 | **€11892** |
| **Other costs** | €1400 | €20314 | €6300 | €0 | **€28014** |
| **Project related publication expenses** | €0 | €750 | €750 | €750 | **€2250** |
| **TOTAL** | €59499 | €87705 | €68513 | €14644 | **€230361** |

## 5. Requested modules/funds

### 5.1. Basic Module

| 5.1.1 FUNDING FOR STAFF | 2024 | 2025 | 2026 | 2027 | Total |
|---|---|---|---|---|---|
| 1 doctoral student TV-L E13 75% | €41681 | €55575 | €55575 | €13894 | **€166725** |
| Hiwi w. BSc degree | €1456 | €2002 | €728 | €0 | **€4186** |
| **Total (yearly and sum for 3 years)** | **€43137** | **€57577** | **€56303** | **€13894** | **€170911** |

**One doctoral student (NN)** will be employed for the duration of the project (3 years), based at the University of Munich, and is supervised by Dr. habil. Simon Kübler (SK). NN will be the primary person responsible for conducting remote sensing and GIS analysis, as well as field mapping and pedo-geological sampling and analysis. A dissertation by NN within the project after 3 years is planned. The position will be announced via common geoscience job portals. The doctoral student should have a background in geology and/or physical geography. Salary (€ 53,775/ year) is

based on *“Personalmittelsätze DFG 2023“* and is following with 75% TV LE13 the common standards in this scientific field (see DFG-Vordruck 55.02 – 05/22).
**One student assistant** (“Hiwi”, with BSc degree) will help compiling digital remote sensing and geological data, and creating a GIS database. Further, the student will help processing geological field samples to prepare them for XRF, OSL and $C^{14}$ analysis. Funds are requested for 1 student 10h/ week for 8 weeks in 2024, 11 weeks in 2025, and 5 weeks in 2026 at the University of Munich. Participation of students in research is an integral part of our undergraduate training. Student assistants will be involved in the project in order to introduce them in scientific working principles already in an early stage of their studies. They will have the opportunity to write a Master thesis in fields related to this project. Salary is based on 2023 wages at the University of Munich of € 18.20/ hour for students holding a BSc degree including „Arbeitgeberanteil“.

| **5.1.2 DIRECT PROJECT COSTS** | | | | | |
|---|---|---|---|---|---|
| **5.1.2.1. Equipment up to € 10,000, Software and Consumables** | **2024** | **2025** | **2026** | **2027** | |
| Multispectral imagery (WW1+2) | €6298 | €0 | €0 | €0 | |
| ERDAS imagine software package (LRZ license) | €435 | €435 | €435 | €0 | |
| Global Mapper GIS Software | €500 | €0 | €0 | €0 | |
| Metashape Pro (academic license) | €549 | €0 | €0 | €0 | |
| **Total consumables (yearly & sum for 3 years)** | **€7782** | **€435** | **€435** | **€0** | **€8652** |

The proposed project includes working with optical and topographic remote sensing data from satellite-based image collections. For the available computing facilities of LMU Munich, Geology, Geoinformation software as well as software for processing and analyzing satellite data and producing photogrammetric 3D models will be purchased. Proposed travel costs include field work and participation in scientific conferences. Additional costs include geological maps, geochronological analyses and field consultant fees.

**Field equipment** includes a soil moisture field analyzer, model *Gilson Speedy 2000* (€ 1822 incl. VAT) will be used to carry out high density soil moisture measurements in the field.
**Software:** ERDAS imagine remote sensing software package will be used to process and analyze multispectral satellite imagery. Single academic license via Leibniz Rechenzentrum (LRZ) is € 435/ year.
Global Mapper Pro, (single desktop license, € 500) will be used to carry out GIS processing tasks, digital mapping and compilation of a geo-pedological GIS database of the study region.
Metashape Pro (single desktop license, € 549) will be used to create 3D surface models of surfaces and outcrops from field photography.

| **5.1.2.2. Travel Expenses *Doctoral Student (NN)*** | **2024** | **2025** | **2026** | **2027** | |
|---|---|---|---|---|---|
| Field work in Tanzania (NN) | €1420 | €4120 | €0 | €0 | |
| International Conferences (NN) | €0 | €937 | €2165 | €0 | |
| **Total Travel NN (yearly & sum for 3 years)** | **€1420** | **€5057** | **€2165** | **€0** | **€8642** |
| **Travel Expenses *Kübler, Simon (SK)*** | | | | | |
| Field work in Tanzania (SK) | €5760 | €2460 | €0 | €0 | |
| International Conferences (SK) | €0 | €1112 | €2560 | €0 | |
| **Total Travel SK (yearly & sum for 3 years)** | **€5760** | **€3572** | **€2560** | **€0** | **€11892** |
| **Total Travel (NN+SK, yearly & sum for 3 years) )** | **€0** | **€8629** | **€4725** | **€0** | **€20534** |

**Field work in Tanzania:** Field work in northern Tanzania will be carried out in 2024 and 2025, for 4 weeks per year. Transportation will be via a 4x4 field vehicle incl. driver, rented at the Nelson Mandela African Institute of Science and Technology - an institute SK has collaborated with since 2018, and that is located proximal to the proposed field locations in northern Tanzania. **Per field campaign, travel expenses in Tanzania** include flights (Munich-Kilimanjaro-Munich) for SK and NN (€ 1000/person), 4x4 rental car incl. driver (€ 770/ week), fuel for ~1500 km (€ 270), accommodation and food costs for SK and NN (€ 420/ week/ person). To avoid extra expenses, field work will be scheduled so that both campaigns are finished within a 12-months period (**Table 1**) to be covered within one set of annual research permits. Permits will be aquired from the Tanzania Commission for Science and Technology (COSTECH, € 300/ person), and the Tanzania Wildlife Research Institute (TAWIRI, € 1000 postdoctoral, € 400 doctoral), as well as a class C visa for researchers (€ 500/ person), and and annual fee for research in critical protected areas (€ 1500).

**International conferences:** 2025: SK+NN will present the first results of the project and the first field campaign at the European Geoscience Union in Vienna, April 2025, 6 days, 5 nights. Requested funds for SK and NN: 2x train tickets Munich-Vienna-Munich (200€/person). Daily allowance: € 24 each travel day, € 36 full day p.P. Hotel: Hotel Kagran near Centre (used during previous stays, 2x € 270/5 nights (single room). 2x Abstract fee € 40, registration fee full/student rates € 390/225, member fee full/student rates € 20/10. 2026: SK+NN will present results of the second field campaign at the Geological Society of America annual meeting in Denver, Colorado, October 2026, 5 days, 4 nights. Requested funds for SK and NN: 2x flight ticket MUC-DEN-MUC € 1200/person economy, transportation to and from airport (approx. € 20/person), registration fee student/full 225/620$, 2x hotel single room € 600/4 nights. Daily allowance: € 24 each travel day, € 36 full day p.P.

#### 5.1.2.3. Visiting Researchers (excl. Mercator Fellows)

Not Applicable

#### 5.1.2.4. Expenses for Laboratory Animals

Not Applicable

| **5.1.2.5. Other costs** | **2024** | **2025** | **2026** | **2027** | |
|---|---|---|---|---|---|
| Certificate “radiation protection officer” group R3 | €0 | €714 | €0 | €0 | |
| Digital geological maps | €1400 | €0 | €0 | €0 | |
| Ar/Ar dating incl. sample shipment | €0 | €4500 | €0 | €0 | |
| Soil XRF analysis incl. sample shipment | €0 | €0 | €2900 | €0 | |
| Rock XRF analysis incl. sample shipment | €0 | €0 | €1400 | €0 | |
| Hydrochemical analysis (NM-AIST laboratory) | €0 | €0 | €400 | €0 | |
| 14C-datings (Gliwize laboratory) | €0 | €3000 | €0 | €0 | |
| OSL-datings (CEZA laboratory) | €0 | €10500 | €0 | €0 | |
| Field consultant, Tanzania | €0 | €1600 | €1600 | €0 | |
| **Total Other Costs (yearly & sum for 3 years)** | **€1400** | **€20314** | **€6300** | **€0** | **€28014** |

**Certificate “Radiation Protection Officer”:** SK will undergo a specialized course in radiation protection, aligned with the R3 activity group's technical guideline (Tätigkeitsgruppe R3). This training is a prerequisite to achieve the Radiation Protection Officer (Strahlenschutzbeauftragter) certification, which is required for using the pXRF analyzer in the field.

**Digital geological maps**: A total of 20 scanned digital geological maps (scale 1:125.000) of Tanzania will be purchased from EastView Geospatial, € 70/map. Georeferencing of digital maps will be carried out by student assistant.

**Ar/Ar dating** of phonolitic rock samples from the hanging wall and footwall of the IUFZ. We expect four samples to be dated. Sample processing, mineral separation and dating will be performed the University of Fairbanks, Alaska, Geochronology Laboratory, which a special price of

1000€/sample, which we have negotiated with the lab manager Prof. Florian Hofmann, a long-time collaborator of our working group.
**Lab XRF analysis**: € 50/sample (internal LMU prices), € 800 sample shipment. To calibrate field XRF measurements, we will export 50 soil samples and 20 rock samples from Tanzania to Germany and process them for main oxide and trace element analysis to the XRF labs at LMU Munich (collaboration with Dr. Donjá Aßbichler and Karin Paschert).
**Hydrochemical analysis** of water samples from rivers, wetlands and thermal springs. We expect 10 samples to be analyzed, particularly targeting fluoride and heavy metal concentrations. Analysis will be performed at the water chemistry labs at NM-.AIST (collaboration with Prof. Machunda and Dr. Said), at the price for international collaborators of € 40/sample (incl VAT).
**AMS $^{14}C$ dating** of plant and charcoal samples from faulted sedimentary layers. We expect 10 samples to be dated. We have been using the $^{14}C$ laboratory at GADAM Centre in Gliwice, Poland with a special price of € 300/sample (incl VAT), which we have negotiated during previous collaborations with Drs. Anna Pazdur, and Adam Michczynski of GADAM centre, respectively.
**OSL dating** of sediments from 4 fault-bounded alluvial fans. We expect 15 samples (3-4 samples per alluvial fan) to be dated. Dating will be performed at the OSL labs at the Curt-Engelhorn-Centre of Archeometry (CEZA) in Mannheim, Germany for € 700/sample, which we have negotiated through Prof. Eileen Eckmeier (german collaborator in the proposed project), who has previously collaborated with CEZA.
*Please be aware that the availability of suitable sampling material directly influences the number of samples for 14C and OSL analysis. Consequently, the exact number of samples for each dating method may vary. Rest assured, any funds allocated for dating will be used judiciously based on the available sampling material.*
**Field consultant for Tanzania:** We will hire a field consultant and for the proposed field campaigns in Tanzania. Consulting fees are € 400/week.

| 5.1.2.6. Project related publication Expenses | 2024 | 2025 | 2026 | 2027 | |
|---|---|---|---|---|---|
| Publication fees open access | €0 | €750 | €750 | €750 | |
| **Total Publications (yearly & sum for 3 years)** | **€0** | **€750** | **€750** | **€750** | **€2250** |

**Open access publishing:** The university of Munich partially supports pure open access publication (Gold standard open access). Costs for the remaining publishing fees (max. € 750) of three manuscripts are requested.

| 5.1.3. INSTRUMENTATION | |
|---|---|
| **5.1.3.1. Equipment exceeding € 10,000** | |

Not Applicable

## 5.2 Module Temporary Position for Principal Investigator

Not applicable

## 5.3 Module Replacements

Not applicable

## 5.4 Module Temporary Substitute for Clinicians

Not applicable

## 5.5 Module Mercator Fellows

Not applicable

## 5.6 Module Project-Specific Workshops

Not applicable

### 5.7 Module Public Relations

Not applicable

### 5.8 Module Standard Allowance for Gender Equality Measures

Not applicable