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An integrated approach to elucidate the recharge and heat source zones in a half-graben geothermal system: An insight from the Songwe geothermal field in southwest Tanzania

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Abstract

Geothermal systems in half-graben settings present unique challenges due to complex geological structures and fluid dynamics. To address these challenges, we utilize a combination of geological, geophysical, and hydrochemical data to develop a comprehensive model that elucidates the system's recharge mechanisms and heat source dynamics, using the Songwe geothermal field in southwest Tanzania as a case study. This research advances the understanding of geothermal processes in half-graben systems and demonstrates the efficacy of interdisciplinary methodologies in identifying and characterizing geothermal resources. The integration of gravity and hydrogeochemical data provides detailed subsurface models, revealing critical faults within the graben zones, which act as conduits for geothermal fluid discharge. Meteoric origin of the fluid is revealed by the stable isotopes $\delta^{18}O$ and $\delta^{2}H$ in the geothermal water. These isotopes also define the recharge zones along fault flanks at elevations of ca. 1400 and 2400 meters above sea level (masl). The geothermal water undergoes dilution and interactions before the discharge. Gravity data analysis further identifies the location of heat sources with low anomalous gravity, which is linked to young magmatic intrusions at depth within the graben. In contrast, high gravity anomalies are observed away from the graben. Our interdisciplinary approach facilitates a comprehensive understanding of the geothermal fluid circulation and heat transfer within the system, aiding in predictive zoning for artificial recharge and strategic resource management. This study not only advances the understanding of geothermal processes in half-graben systems but also demonstrates the effectiveness of employing interdisciplinary methodologies in identifying and characterizing geothermal resources.

1 INTRODUCTION

In rift settings, particularly within graben systems, careful strategies are required to delineate recharge zones through common approaches, including GIS and remote sensing, geological and hydrological studies, geochemistry, geophysics, and exploratory drilling. Among them, geochemical data are crucial for identifying recharge areas: chemical and isotopic tracers can confirm connections between recharge zones and geothermal systems, and solute/isotope modeling can simulate fluid pathways and estimate recharge-zone characteristics in a graben (Zhou et al., 2023; Liu et al., 2024).

Gravity surveys have been widely used to characterize the structure and subsurface geometry of geothermal systems, including heat sources and discharge zones. Gravity anomalies can indicate higher-permeability areas where recharge may occur (Mulugeta et al., 2021). By integrating geological, hydrological, and geochemical data, gravity data improves the understanding of subsurface conditions, improving recharge zone delineation (Lautze et al., 2017).

In rift settings, particularly half-grabens, targeted methods are required to delineate recharge and heat-source zones. This study applies a multidisciplinary, integrated approach to the Songwe Half Graben Geothermal Prospect (SHGGP) to assess its recharge and heat source. Songwe was selected because it lies within the tectonically active East African Rift, exhibits surface thermal manifestations and favorable structural controls for fluid flow, has promising shallow temperature and spring geochemistry data, and is under-explored relative to other rift prospects, making it a high-priority site for assessing exploitable geothermal potential. (Fig. 1).

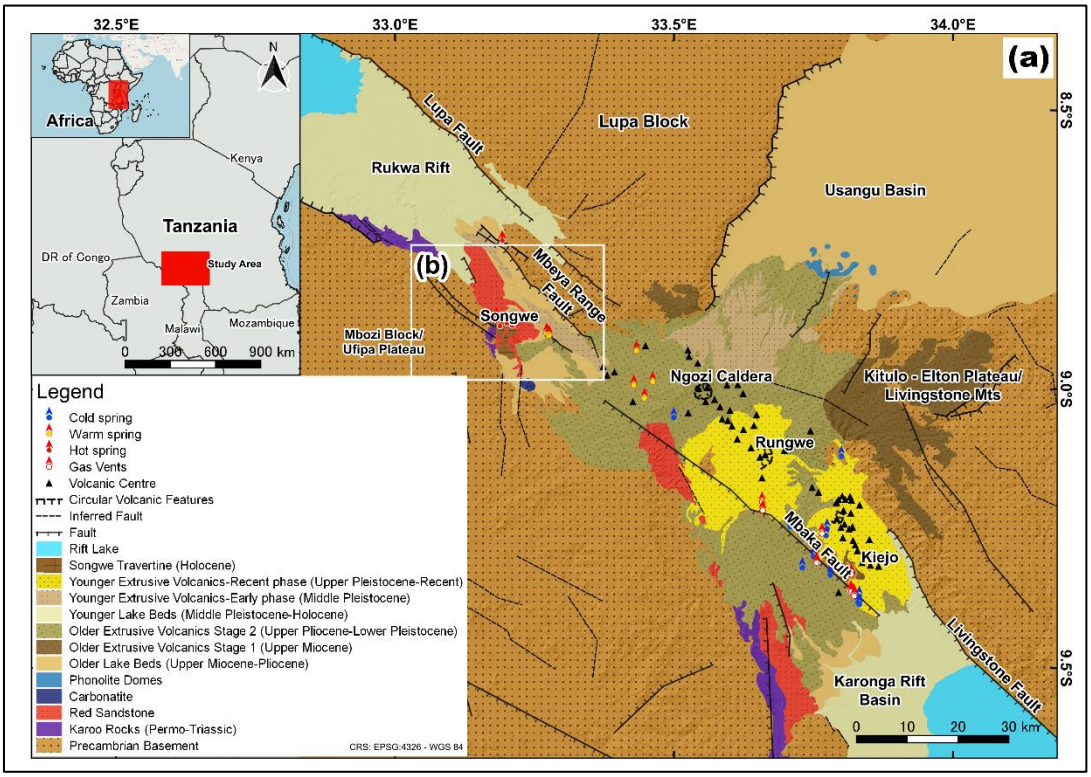


Figure 1. (a) Geological map of the Rungwe Volcanic Province (RVP), modified from Fontijn et al. (2012) and Kobare et al. (2025), overlaid on a hillshade digital elevation model (DEM) to highlight structural features and lineaments, and (b) the Songwe half graben depicted on a rectangle showing sample locations and clustered manifestations, predominantly along travertine ridges and Cretaceous sandstone units.

2 MATERIALS AND METHODS

This study employs an integrated approach that combines geochemical and geophysical datasets, as described in the following subsections.

2.1 Sampling and Analysis

Systematic sampling for geochemical data collection was conducted from August 2023 to September 2024. Physico-chemical parameters, including temperature (°C), estimated discharge (E.D) in Liters per second (L/s), electrical conductivity (EC) in microsiemens per centimeter (µS/cm), total dissolved solids (TDS), dissolved oxygen (D.O), oxidation reduction potential (ORP), and pH, were measured on-site. The concentrations of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) anions were directly measured in the field through alkalinity titration, with results recorded as total alkalinity in terms of HCO_3^-. The $\delta^{18}O$ and $\delta^{2}H$ isotopes were measured using a high-precision water isotope analyzer (Picarro L2140-i) in the authors' laboratory.

2.2 Gravity Data Modeling

Gravity data used were downloaded from TOPEX and processed as follows. Bouguer and free-air gravity anomalies were calculated and then corrected for known effects (terrain, elevation, and latitude). Vertical and horizontal derivatives were derived by differentiating the modeled gravity field. The vertical derivative highlights shallow vertical density contrasts and sharpens edges of near-surface sources. Horizontal derivatives computed for north-south and east-west gradients, as well as the total horizontal gradient, emphasize lateral discontinuities such as fault zones or lithologic contacts. Derivatives were computed in the spatial domain using finite-difference operators on gridded gravity data. These derivative maps were interpreted together with the density model (Fig. 2) and other geological data to identify heat source zones, structural controls, and hydrothermal patterns relevant to geothermal exploration.

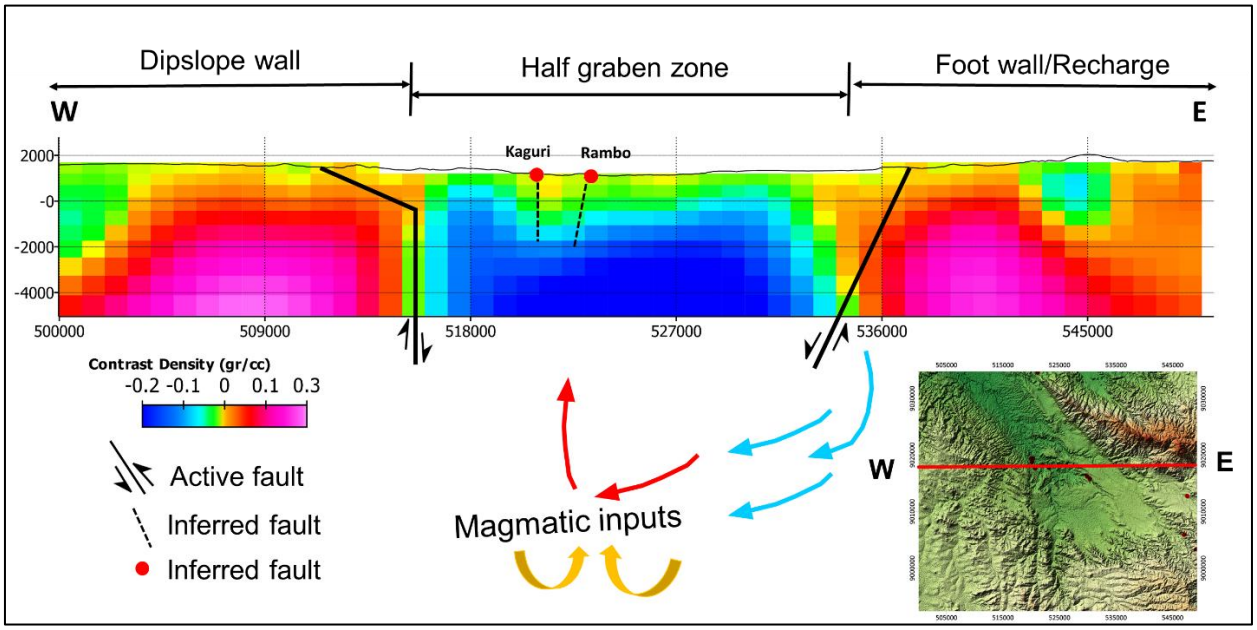


Figure 2. A vertical cross-section from the 3D inversion result highlights high-density zones located away from the graben, whereas low anomalous gravity is in the graben.

3 RESULTS AND DISCUSSION

The recharge elevation derived from the hydrochemical data of the samples within the half-graben system ranges approximately from 1,400 to 2,400 masl (Fig. 3). Beneath depths of about 3,000 meters below sea level (mbsl), recharge waters are primarily modified by temperature-dependent water–rock interactions at depth, which then appears in surface manifestations through active faults at the central part of the graben. When isotope ratios indicate significant evaporation or enrichment, this suggests shallow recharge under arid conditions or surface mixing with steam loss. Conversely, depleted isotopic values originate from high-altitude recharge and deeper circulation pathways (Kobare et al., 2025). The extent of $\delta^{18}O$ enrichment relative to $\delta^{2}H$ divergence acts as a key indicator: pronounced $\delta^{18}O$ enrichment with minimal $\delta^{2}H$ change typically signifies high-temperature isotopic exchange within the reservoir, with little influence from non-meteoric water inputs.

In the Songwe geothermal system, gravity data elucidate the primary structural framework governing the fluid flow system and reservoir architecture. Broad gravity lows correspond to thick, low-density sediments in the graben, whereas linear gravity gradients and localized highs correspond to uplifted rift shoulders, buried basement highs, and dense intrusive bodies (Mulugeta et al., 2021). Bouguer density contrast patterns are consistent with a hot plume, interpreted as the probable heat source emplaced within the graben and overlying a fractured, permeable crystalline metamorphic basement. Gravity and geomorphological features identify normal border faults and intra-graben faults, which facilitate downward recharge from the flanks and upward flow within the graben. In Songwe, the gravity patterns suggest an asymmetric basin with steep fault-bounded margins, both acting as permeability pathways and as structural traps or compartmentalized reservoirs. The western and northeastern sides of the graben display evidence of older intrusions or dense basement protrusions, which form both heat sources and recharge conduits (Fig. 2).

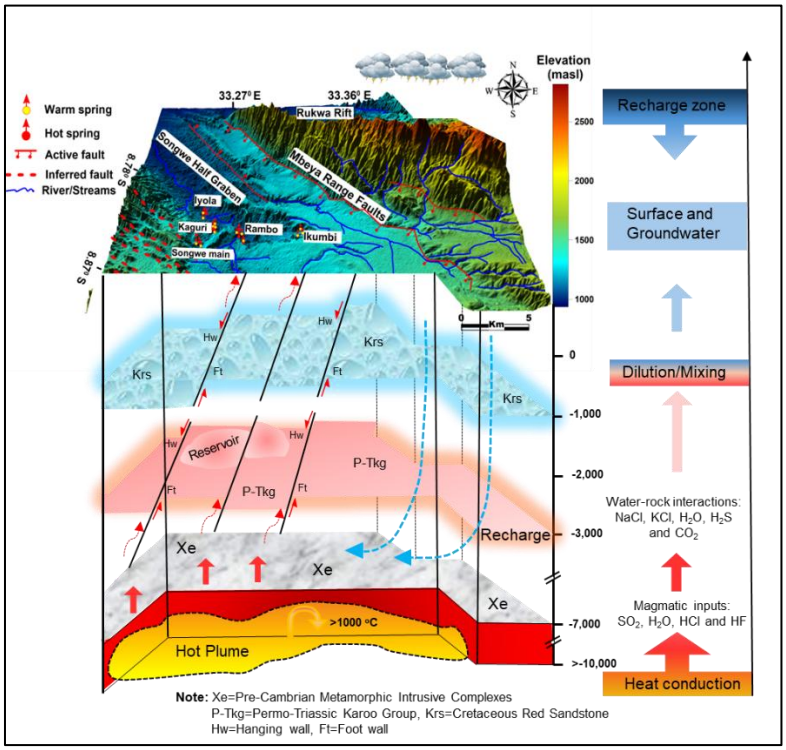


Figure 3. The conceptual model of a geothermal system showing a recharge zone and a heat source that drives the geothermal fluids within the Songwe half-graben system.

4 CONCLUSION

This study combines gravity, geological, and hydrochemical data to uniquely resolve recharge zones, flow paths, and deep heat sources in a half-graben geothermal system. It demonstrates that Songwe's geothermal fluids are meteoric, recharge along fault flanks at ~1400–2400 masl, and undergo dilution and rock interaction during ascent. Gravity anomalies pinpoint low-density zones consistent with young magmatic intrusions beneath the graben, providing the first integrated subsurface model that links structural conduits to heat supply and informs targeted exploration and resource management.

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