Exploring the geothermal potential in the Himalaya-Karakoram Orogenic belt of northern Pakistan

Muhammad Anees[1, 2*], Jonas Kley[1], Bernd Leiss[1], and Mumtaz M. Shah[3]

[1]*Department of Structural Geology and Geothermics, Georg-August-Universität Göttingen, Germany;*

[2]*LIAG Institute for Applied Geophysics, Hannover, Germany;*

[3]*Department of Earth Science, Quaid-i-Azam University Islamabad, Pakistan*

[*]*Email: muhammad.anees@stud.uni-goettingen.de*

Northern Pakistan, situated within the collision zone of the Indian and Asian plates, encompasses the Himalaya, Kohistan, and Karakoram regions, hosting numerous hot springs linked to the Himalayan Geothermal Belt stretching 3000 km along the Himalayas. Understanding the magnitude of terrestrial heat flow and characteristics of potential heat sources in this belt is crucial across geoscientific domains. However, geothermal exploration in this remote area faces challenges due to limited data, with only two decades-old geochemical analyses of hot springs available. The absence of reliable geophysical data and petrophysical parameters hinders understanding the lithosphere's thermal state, essential for geothermal modeling. This study aimed to evaluate geothermal resources in the Himalaya-Karakoram region of Pakistan at a reconnaissance level, offering baseline data and pinpointing zones for future detailed exploration. Employing a multi-method and multi-scale approach, the study commenced with a regional- level investigation using remote sensing, geological mapping, and literature review to analyze tectonic mechanisms, structural features, surface temperature patterns, and hydrothermal alterations. Ground-based measurements of radioelement concentrations were conducted using a portable gamma spectrometer, complemented by laboratory analyses (XRD, optical and cathodoluminescence microscopy, XRF, and ICP-MS) of altered and unaltered samples to determine mineralogical, petrological, geochemical, and petrophysical properties. Remote sensing results confirmed high lineament density, thermal anomalies, and hydrothermal alteration near hot springs and suture zones. Hydrothermal alteration detected via remote sensing

was validated by XRD analysis, laying the groundwork for subsequent field investigations. Radiogenic heat production was found to be high in the Nanga Parbat Massif (> 4 μWm^{-3}), moderate in the Karakoram batholith (2 – 4 μWm^{-3}), and low in the Kohistan-Ladakh batholith (< 2 μWm^{-3}). Geochemical analyses unveiled peraluminous S-type gneisses and granites in the Nanga Parbat Massif, syenitic to granitic compositions with REE-rich allanites in the Karakoram batholith, and calc- alkaline I-type granitoids with REE and radiogenic element depletion in the Kohistan-Ladakh batholith. The granitoids and gneisses exhibited weak to moderate alteration of biotite, K-feldspar, and plagioclase, intensifying towards intensely deformed zones. The genesis of hot springs is attributed to high geothermal gradients from elevated radiogenic heat production and exhumation, accessed by meteoric waters through deep faults. The Nanga Parbat region, central Karakoram, and eastern Karakoram are identified as potential geothermal targets for detailed investigations, with hydrothermal and hot-dry rock geothermal play types proposed in these areas. Short to long-term strategies for geothermal resource development are outlined, prioritizing the cost-effective and expeditious development of hot spring sites for direct-use applications. Despite existing financial and technical hurdles, the region's geothermal prospects offer substantial promise. This study's findings provide crucial data for comprehending the region's geothermal dynamics on a broader scale and lay the groundwork for future geothermal exploration endeavors.