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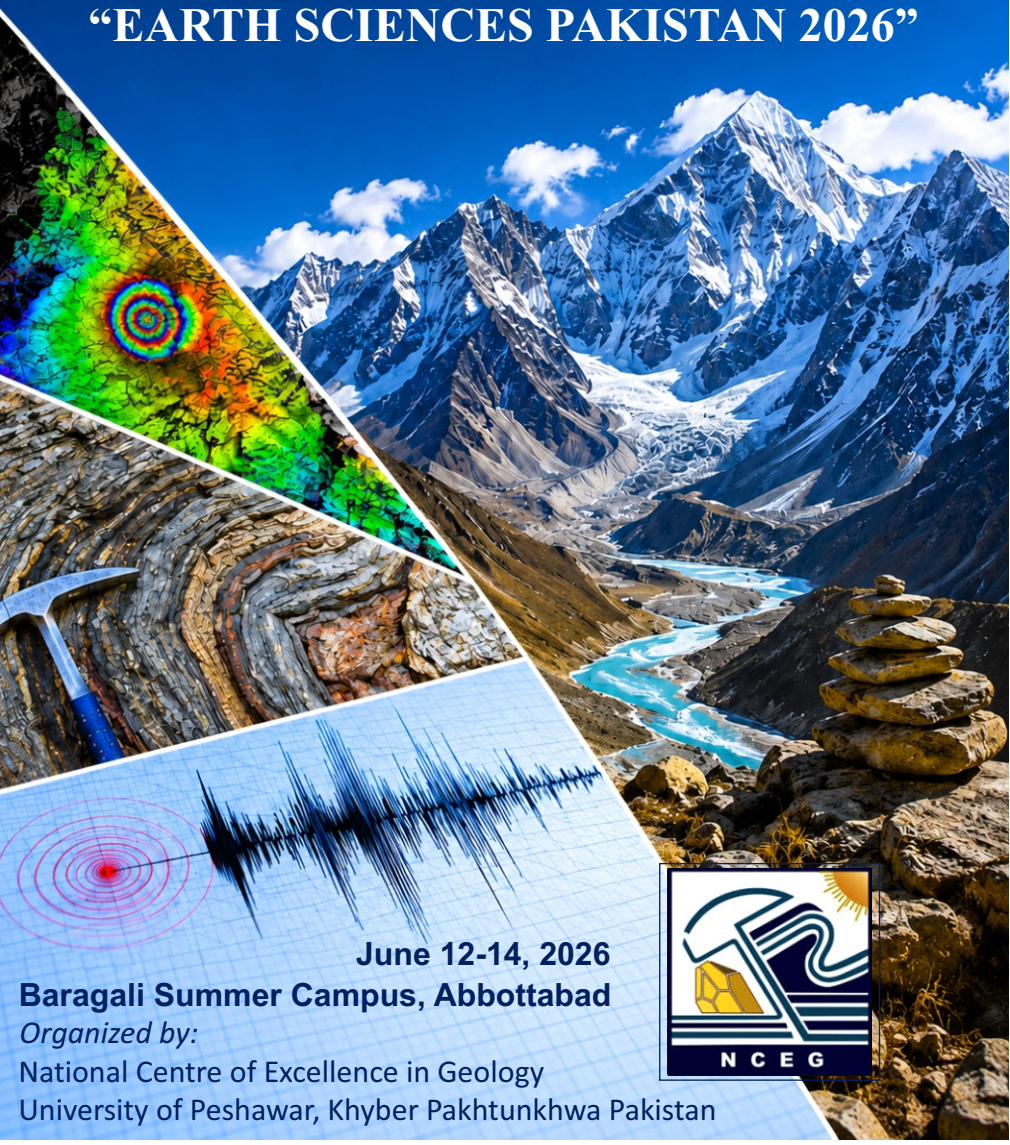
BOOK OF ABSTRACTS

8TH INTERNATIONAL CONFERENCE "EARTH SCIENCES PAKISTAN 2026"



June 12-14, 2026

Baragali Summer Campus, Abbottabad

Organized by:

National Centre of Excellence in Geology

University of Peshawar, Khyber Pakhtunkhwa Pakistan

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(ESP-2026)

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8th International Conference on "Earth Sciences Pakistan" (ESP-2026)
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Proofread by: Dr. Maryum Ibrar (PASTIC)
Edited By: Prof. Dr. Liaqat Ali (NCEG), Prof. Dr. Khalid Latif (NCEG), Ms. Rahila Khurram (PASTIC)
Composed by: Dr. Waqas Ahmed (NCEG), Ms. Shazia Parveen (PASTIC)
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PREFACE

Since its establishment in 1974, the National Centre of Excellence in Geology (NCEG) has remained at the forefront of higher education and research in geosciences in Pakistan. In addition to its core mandate of academic excellence, NCEG has consistently promoted intellectual exchange and scholarly discourse through the organization of conferences, seminars, and workshops spanning diverse fields of geosciences. Among these initiatives, the International Earth Sciences Pakistan (ESP) conference stands as a flagship event, widely recognized for its scientific impact and academic rigor. The inaugural ESP conference was held in 2010, followed by successful editions in 2012, 2014, 2016, 2018, 2022, and 2024.

Over the years, the ESP conference series has evolved into a premier scientific platform for dialogue, collaboration, and innovation in earth sciences. It has earned national and international recognition, attracting leading scientists, researchers, and professionals from academia, industry, and government institutions. Each successive edition has expanded its thematic breadth and scientific depth, contributing meaningfully to the advancement of geoscientific knowledge and its applications.

ESP -2026 continues this tradition as a multidisciplinary forum addressing contemporary challenges and emerging frontiers in geosciences. The conference encompasses a wide range of thematic areas, including mineral exploration, processing and sustainable mining; structural geology and tectonics; engineering geology, geotechnical engineering and construction materials; applied geophysics and subsurface imaging; geoinformatics, remote sensing, natural hazards and disaster risk reduction; energy, petroleum systems and basin analysis; environmental and soil sciences, climate change and hydrology; and sedimentology, palaeontology, mineralogy and petrology.

By facilitating high-level scientific presentations and discussions, ESP -2026 aims to stimulate new research directions, foster interdisciplinary collaboration, and strengthen the interface between science, industry, and policy. The conference also provides a valuable platform for the corporate sector to showcase technologies, products, and services, while engaging with more than 500 researchers, stakeholders, and policymakers from within the country and abroad. This interaction enables meaningful networking and access to a wide range of scientific and technical sessions.

In response to the call for abstracts for ESP-2026, more than 100 submissions were received from academics, graduate students, and professionals representing both academia and industry across various domains of earth sciences. Each submitted abstract has undergone peer review by at least two referees to ensure scientific quality, relevance, and rigor.

Prof. Dr. Liaqat Ali, Convener, ESP 2026
Prof. Dr. Khalid Latif, Chief Organizer, ESP 2026
Dr. Waqas Ahmed, Co-Chief Organizer, ESP 2026
Dr. Sarfraz Khan, Conference Secretary, ESP 2026

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The Pakistan Scientific & Technological Information Centre (PASTIC) is a constituent organization of the Pakistan Science Foundation (PSF) operating under the Ministry of Science and Technology (MoST), Government of Pakistan. PASTIC is a premier national institution specialized in the collection, organization, management, and dissemination of Scientific and Technological Information (STI) to support research, development, and industrial innovation across the country.

The PASTIC National Centre is located at the Quaid-e-Azam University Campus, Islamabad, with a nationwide network of six Sub-Centres in Karachi, Lahore, Peshawar, Quetta, Faisalabad, and Muzaffarabad, ensuring broad regional outreach.

Since its inception, PASTIC has played a pioneering role in supporting Pakistan's research community, particularly during the early stages of national S&T infrastructure development. Its services historically included the supply of scientific and technical literature, abstracts and indexes, bibliographies, translations, patent information, science reference library services, technological information transfer, computer-based information dissemination, and reprographic and publication services.

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- Collaboration & Cooperation with institutional libraries/repositories for resource sharing
- Promotion of R&D based industrial development
- Printing of S&T/R&D Publications
- Capacity/skill development of researchers, information professionals, innovators & entrepreneurs
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PASTIC Functions

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- *Abstract Books of Conferences*: PASTIC supports publication/printing of Abstract Books of Conferences organized by various S&T universities (on request).

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- PakCat: Union Online Public Access Catalogue (OPAC) of books available in Scientific & Technological Libraries of Pakistan
- Digital Repository of Indigenous S&T literature
- Directory of Scientific Periodicals of Pakistan: An index of scientific periodicals (e.g., Journals, Magazines etc.) published in Pakistan.
- Database of R&D Projects executed in Pakistan
- Database of Books published by Pakistani authors
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Organize Seminars/Workshops /Trainings/ for capacity building of:

- Young Researchers on Data analysis, Reference Management etc.
- Women Entrepreneurs on E-marketing &E-business skills
- Library Professionals on Library automation & digitization
- Journal Publisher/Editors on E-Journal management & publishing
- Researchers and Innovators on Intellectual Property Rights, Media Information Literacy

CONFERENCE PROGRAM

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Conference Session 2 (Hall A)	**Conference Session 3 (Hall B)**
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Conference Session 4 (Hall A)	**Conference Session 5 (Hall B)**
Applied Geophysics & Subsurface Imaging	Geoinformatics, Remote Sensing, Natural Hazards & Disaster Risk Reduction
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ABSTRACTS

Theme 1: Mineral Exploration, Processing & Sustainable Mining

Plate Tectonics and Mineralization in Pakistan: Insights into Geological Evolution and Resource Potential

M. Qasim Jan[1,2*] , Rahat Ullah[3*]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]China-Pakistan Joint Research Centre on Earth Sciences, Islamabad, Pakistan; [3]Geological Survey of Pakistan, Quetta/Islamabad, Pakistan

[*]Email: mqjan@yahoo.com; rahatullah238@gmail.com

Pakistan lies at the junction of three major tectonic plates, the Indian, Eurasian, and Arabian, resulting in diverse and unique geological settings. Its complex history, from the Paleo-Proterozoic to the present, includes the breakup of Gondwana, the northward drift of India, island arcs development, continental collision, fold-thrust belts generation, and ophiolite obduction (Molnar & Tapponnier, 1977; Kazmi & Jan, 1997). These plate interactions resulted in multiple episodes of magmatism, sedimentation, and metamorphism, creating favorable conditions for mineralization across various petrogenetic domains. Among the many identified mineral deposits, the more significant ones include: 1) Metallic minerals comprising copper–gold deposits at Reko Diq (5.5 Bt), Saindak (2.2 Bt), Siah Dik and other ~48 deposits all over the Chagai District, low- to mediumgrade iron ore at Chiniot, Dilband, and Kalabagh (approximately 150, 200, and 300 Bt, respectively), chromite deposits exceeding 5 Mt of mainly metallurgical grade occurring in scattered locations, and lead–zinc ±barite deposits at Duddar and Gunga (>50 Mt); 2) Industrial minerals and rocks include resources of rock salt, gypsum, limestone, and dolomite (very large to large), along with large deposits of china/fire clays; 3) Abundant decorative stones, including large amount of marble, granite, gabbro-diorite, travertine, and basalt; 4) Building materials are available in very large amounts; 5) Globally recognized large variety of high quality gemstones such as emerald, ruby, aquamarine, topaz, tourmaline, garnet, and peridot, etc., primarily found in the northern part of the country, and 6) 175 Bt of lignite in Thar. Here we describe the principal mineral deposits of Pakistan and their tectonic configuration.

Keywords: Plate tectonics; Metallic minerals; Industrial minerals; Gemstones; Reko Diq; Saindak; Thar

The Origin of Gemstones and Their Resource Potential for Revitalizing the Natural Resource Economy of Pakistan

Tahseenullah Khan

Department of Earth and Environmental Sciences, Bahria University, H-11 Campus, Islamabad, Pakistan

Email: tkhan.buic@bahria.edu.pk

The Karakoram, Hindukush, and Himalayan Mountain ranges are located in the northern region of Pakistan. The Himalayas represent the margin of the Indo-Pak (Indian) continental plate, whereas the Karakoram and Hindukush ranges are associated with the Eurasian (Asian) continental plate. Situated between these two major continental blocks is the Kohistan Island arc terrane, which is tectonically bounded by two major suture/thrust systems: the Main Mantle Thrust (MMT) to the south and the Main Karakoram Thrust (MKT) to the north. These geological units are predominantly exposed across northern and northeastern Khyber Pakhtunkhwa (KP) and Gilgit-Baltistan (GB). Gemstone mineralization in the region is hosted within both continental crustal domains as well as the intervening suture zones, particularly the MMT belt. These gemstone deposits are the product of complex geological evolution, primarily associated with igneous–hydrothermal processes and regional metamorphism linked to the collisional tectonic history of the Himalayan orogen. Pakistan is a vast country with considerable wealth in natural resources, and the understanding Pakistan's geology is critical for efficient exploration and exploitation of these resources. Estimates for copper and iron ore resources were found to have the most potential for extraction in Pakistan. Likewise, gemstone resource potential represents a critical sector that cannot be ignored in national development planning. There are four main gemstone-producing areas in Pakistan: The Swat Valley, producing emeralds; the Hunza and Neelum Valleys, producing the world-famous and most recognized of ruby gemstones; the Naran Valley, famous for ruby, peridot and demantoid garnets; and the Shighar Valley, producing a wide range of gemstones such as tourmaline, topaz, and aquamarine. Gemstone mining in Pakistan is typically an artisanal activity carried out by people living in villages surrounding the mines. Tunnels are excavated, and gems are extracted by hand using drills and explosives. These practices result in significant waste, damage to gemstones, and ultimately low recovery yields. Pakistan is also renowned for producing high-quality gemstone specimens that are highly valued by international collectors, with exceptional specimens often commanding premium prices in global gem and mineral markets. Many Pakistani gemstone specimens are regularly displayed at international gem shows and traded through online platforms. However, a substantial proportion of Pakistan's gemstones are exported through informal or illicit channels, with an estimated 70–80% routed to neighboring countries for grading and quality sorting. Lower-grade stones are typically processed for the domestic market, whereas medium- and high-quality gemstones are exported onward to international cutting and polishing centers that cater to Western

markets. As a result, Pakistan captures only a limited share of the value chain, losing opportunities for value addition, export earnings, employment generation, and technological development. This informal trade structure also makes it difficult to accurately assess the true economic value of the country's annual gemstone production. Pakistan possesses significant potential to expand its share in the global gemstone market, owing to its strategic proximity to India and Thailand as well as the rising international demand for high-quality gemstones in North America, Europe, East Asia, and the Middle East. The country's rich gemstone resources present a valuable opportunity for sustainable economic development and the revitalization of the natural resource sector. By adopting advanced exploration and processing technologies, promoting value addition, strengthening regulatory frameworks, and developing local technical expertise, Pakistan can enhance the competitiveness of its gemstone industry, attract foreign investment, generate employment opportunities, and establish a stronger presence in the global gemstone market.

Keywords: Gemstone deposits; Karakoram–Himalaya–Hindukush; Main Mantle Thrust; Kohistan arc; Artisanal mining

Opportunity to Transform Untapped Mineral Resources for Sustainable Economic Growth and Development of Pakistan

Asghar Karim

Punjab Mineral Company, Government of Punjab, Pakistan
Email: ceo@pmc.punjab.gov.pk

Pakistan possesses vast untapped mineral resources, including iron ore, copper, gold, coal, industrial minerals, and construction materials, which present a significant opportunity for sustainable economic growth and national development. These resources have the potential to support industrialization, enhance exports, create employment opportunities, attract local and foreign investment, and reduce dependence on imported raw materials. However, despite this immense potential, the mineral sector in Pakistan remains underdeveloped due to limited exploration activities, fragmented geological data, outdated mining practices, and insufficient technological and institutional capacity. The effective exploration, evaluation, and responsible development of mineral resources can serve as a catalyst for the growth of key industries such as steel, cement, energy, infrastructure, and manufacturing. Strategic initiatives such as the Chiniot Iron Ore Project demonstrate the important role of mineral development in promoting industrial expansion and long-term economic value creation. In this transformation process, geologists play a strategic role through the identification and evaluation of mineral resources, generation of reliable geological data, reduction of exploration risks, and enhancement of investor confidence through internationally recognized standards and modern exploration techniques. Sustainable mineral development, however, requires a balanced approach that integrates economic progress with environmental protection, social responsibility, and community development. The adoption of advanced technologies, digital mineral data systems, GIS-based resource management,

and transparent regulatory frameworks can significantly improve the efficiency, transparency, and investment attractiveness of Pakistan's mining sector. By strengthening institutional support, promoting sustainable mining practices, and encouraging investment, Pakistan can successfully transform its untapped mineral wealth into a foundation for long-term economic growth, industrial development, and national prosperity.

Keywords: Mineral resources; Sustainable economic development; Mineral exploration; Mining sector development; Geological data management; Pakistan mining industry

Integrated Remote Sensing, Petrographic, Mineralogical and Geochemical Constraints on Gold-Sulfide Mineralization and Tectono-Magmatic Evolution of the Atud-Um Khasila Area, Egyptian Nubian Shield

M. Hassan Ghoneim[1], Mohamed Zaki Khedr[1], M. Shahab[2*] , Fahad Alshehri[2]

[1]Ashgill Australia Pty Ltd, Level 9, 444 Collins Street, Melbourne, Victoria 3000, Australia; [2]Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, King Saud University, Saudi Arabia

[*]Email: mshahab.c@ksu.edu.sa

This study presents an integrated geological, structural, remote sensing, petrographic, mineralogical, and geochemical investigation of the Atud–Um Khasila area in the Central-Southern Egyptian Nubian Shield, with emphasis on lithological discrimination, tectono-magmatic evolution, and the origin of gold–sulfide mineralization. The study combines field observations, petrography, whole-rock geochemistry, mineral chemistry, and multispectral satellite data from Landsat8, Sentinel2b, and ASTER to refine regional and detailed geological mapping, identify hydrothermal alteration zones, and reassess the metallogenic significance of the Atud–Um Khasila ophiolitic and island-arc assemblages. The remote sensing results successfully delineate major lithological units and alteration patterns, particularly silicification, hematization, carbonate alteration, phyllic, argillic, and propylitic zones, which are spatially associated with structurally controlled mineralization along NW–SE Najd-related shear zones. The investigated mafic intrusive rocks are represented by two main plutonic suites: the older meta-gabbro–diorite complex and the younger Gabal Atud gabbros. The meta-gabbro diorite complex consists mainly of meta-gabbros, diorites, and quartz diorites, whereas the Gabal Atud gabbros are dominated by olivine gabbro intruding the former assemblage. Mineralogical and geochemical evidence indicates that these intrusions record distinct magmatic histories and tectonic settings. The meta-gabbro diorite rocks show calc-alkaline affinities and are interpreted to have formed in a volcanic arc environment, whereas the Gabal Atud gabbros crystallized from Mg-rich tholeiitic melts in an extensional rifted-arc setting, probably related to asthenosphere upwelling triggered by slab detachment and/or lithospheric delamination. Their enrichment in large-ion lithophile elements and light rare earth elements relative to high-field-strength elements suggests derivation from

a metasomatized mantle source modified by earlier subduction-related processes. Thermobarometric estimates indicate crystallization under relatively high oxygen fugacity conditions, with temperatures of approximately 900–1100°C and pressures averaging about 6 kbar, corresponding to depths near 18 km. There are two distinct types of sulphide mineralization. Magmatic Cu–Ni–Fe sulphides, primarily dispersed pyrrhotite, pentlandite, chalcopyrite, and pyrite, which can reach up to 5 vol.%, are found in the Gabal Atud gabbros. The mineralization of the Atud gold mine, on the other hand, is genetically and spatially associated to the meta-gabbro diorite complex. It is represented by hydrothermal sulphide assemblages that can reach up to 30 vol.%, which include native gold, pyrite, arsenian pyrite, arsenopyrite, and minor sphalerite and galena. Gold mineralization mostly takes place in carbonate-silicified zones, metasomatized meta-gabbro, and quartz veins, where Au can reach up to 25 g/t. The mineralized fluids are thought to have come from mixed magmatic–metamorphic sources since they were enriched in Si, K, Fe, Pb, Ag, Au, As, S, Ni, Zn, Cu, CO_2, and H_2O. Together with pyrite and arsenopyrite crystallization, which decreased Sulphur activity and destabilized dissolved gold complexes, fluid–rock interaction between Fe-rich meta-gabbro diorites and Au-bearing bisulfide complexes probably encouraged gold precipitation. The mantle section of the Atud–Um Khasila ophiolite consists mainly of serpentinized and carbonatized harzburgites, locally transformed into ophiocarbonates and listvenites. Their depletion in Al_2O_3, TiO_2, and CaO, combined with enrichment in MgO, Ni, Cr, and Co, indicates derivation from a highly depleted mantle source after high degrees of partial melting, estimated at approximately 15 to >25%, in a forearc setting. This interpretation is further supported by high-Fo olivine, high-Mg# clinopyroxene, elevated Cr# spinel, and oxygen fugacity and temperature conditions comparable to global forearc peridotites. Enrichment in fluid-mobile elements relative to high-field-strength elements reflects intensive metasomatism by slab-derived fluids. Carbonation, listvenitization, and later silica–carbonate alteration was driven by CO_2-rich and Si–Ca–Sr-bearing hydrothermal fluids, most likely derived from subducted sediments or meta-sediments, as indicated by depleted $\delta^{13}C$ and elevated $\delta^{18}O$ values in magnesite. Structurally, the Atud–Um Khasila area records a complex deformational history involving both ductile and brittle structures, including foliations, lineation's, folds, faults, and shear zones. Three structural domains and three deformation phases are identified: early NNW–SSE shortening with top-to-NNW nappe translation, followed by WNW–NW sinistral transpression and E–NE dextral transpression. The latter two phases are linked to Najd Fault System activity. Overall, the study demonstrates that gold–sulfide mineralization in the Atud–Um Khasila area resulted from the interaction of arc-related magmatism, mantle metasomatism, hydrothermal fluid circulation, and Najd-related transpressional deformation, highlighting the area as an important target for future mineral exploration in the Egyptian Nubian Shield.

Keywords: Gabal Atud gabbros; Egyptian Nubian Shield; Gold–sulfide mineralization; Hydrothermal alteration; Ophiolite; Najd Fault System

Geological Framework and Mineral Prospectivity of the Central Chagai Arc, Balochistan: Implications for Porphyry Cu–Au Mineralization

Naseer Uddin[1], Inayat Ullah[1,2*], Abdul Ghaffar[3], Shucheng Tan[4], Muhammad Ishaq Kakar[1], Shams Uddin[1,3] , Shah Wali[1]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Quetta 87550, Pakistan; [2] State Key Laboratory for Critical Mineral Research and Exploration, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China; [3]National Resources Pvt. Limited, Karachi 75500, Pakistan; [4]School of Earth Science, Yunnan University, Kunming 650500, Yunnan, China

[*]Email: inayat.cem@um.uob.edu.pk

The Central Chagai Arc (CRA) in western Balochistan, Pakistan, constitutes a significant part of the Tethyan Metallogenic Zone. This magmatic zone is identified as an Andean-type arc that formed in response to the subduction of the Neo-Tethyan oceanic crust beneath the Afghan Block. This study examines the geological characteristics and mineral potential with emphasis on tectonic evolution, magmatism, and hydrothermal systems. Our study focuses on the Ting Darguan, Machi and Zirathi prospects in CRA. These prospects are surrounded by diverse volcanic and plutonic rocks, such as andesite, dacite, diorite and granodiorite with a late magmatic phase of porphyry intrusions. Further, structural features such as thrust and normal faults, fractures, and intrusive contacts provided favorable pathways for mineralized fluids. Potassic, phyllic, and propylitic hydrothermal alteration zones are well developed within these prospects. The field data and detailed petrographic and ore-microscopic characteristics indicate that these prospects are prominent mineralized zones for porphyry Cu-Au deposits. Further, this study underscores the metallogenic potential of CRA, and it remains a promising location for future exploration and regional resource development.

Keywords: Central Chagai Arc; Porphyry Cu-Au deposits; Hydrothermal alteration; Tethyan Metallogenic Zone; Mineral exploration

Geological and Mineralogical Characteristics of the Khargoshkan Barite Deposit (KBD), Ras Koh Arc, Balochistan, Pakistan: Implications for Mineral Exploration

Shaheen Khan[1], Inayat Ullah[1,2*], A. Shah[1,3], Fida Murad[1], Abdul Ghaffar[4], Waris Khan[1]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan; [2]State Key Laboratory of Critical Mineral Research and Exploration, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China; [3]State Key Laboratory of Lithospheric and Environmental Coevolution, University of Science & Technology of China, Hefei 230026, China; [4]National Resources Pvt. Limited, Karachi 75500, Pakistan

[*]Email: inayat.cem@um.uob.edu.pk

This study provides the first detailed geological and mineralogical characterization of the Khargoshkan barite deposit (KBD), located 60 km SW of Dalbandin in the RasKoh arc, Pakistan. The barite deposit features structurally controlled veins within andesitic rocks of the Paleocene Rakhshani Formation. The RasKoh arc is a major segment of the Tethyan tectonic domain in western Pakistan. It was formed by the northward subduction of the Neo-Tethys Ocean beneath the Afghan block during the Late Cretaceous to Paleogene period. The arc includes Jurassic–Paleogene volcanic and volcaniclastic rocks, ophiolitic mélanges, and intrusive complexes. Volcanic units, such as the Paleocene Rakhshani Formation (containing andesite, basalt, and related pyroclastics), offer a favorable lithological environment for epithermal and mesothermal vein-type mineralization, including barite, due to their natural permeability and reactivity. However, the barite potential of this extensive volcanic region remains nearly undocumented in scientific research. The recently discovered Khargoshkan barite deposit, located about 60 km southwest of Dalbandin city, represents an unmapped, fault-controlled vein system within this underexplored arc. Active mining near Khargoshkan highlights its economic significance for the local and regional economy; however, no previous scientific studies have been conducted to characterize its geology, genesis, or mineralogy. The research studies were carried out both on the base of field and lab analysis. A comprehensive field investigation was conducted at the Khargoshkan barite deposit to clarify the structural controls, the spatial relationships between ore minerals and host rocks, and to describe their macroscopic features. A subset of 10 representative samples was selected for detailed microscopic analysis; Petrographic examinations were conducted. Observations focused on identifying mineral assemblages, textural relationships (e.g., replacement, infill, zoning), grain size and morphology, and paragenetic sequences to distinguish between hypogene and supergene mineralization processes. To determine the chemical composition and micromorphology of the barite and associated phases, detailed analysis was performed using a JEOL JSM-IT200 scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) system. Quantitative EDS was performed using a standardless approach in the JEOL Analysis Station software, estimating elemental concentrations through built-in fundamental parameter (FP) models without external standards. The oxide weight percentages (such as BaO and SO_3) were automatically derived based on stoichiometry. Bulk mineralogical identification and semi-quantitative phase analysis were conducted using X-ray powder diffraction (XRD) The deposit is characterized by three concentric zones: an argillic alteration zone dominated by illite/smectite (25–30 m × 1500 m), a ferruginous gossan (20–30 m × 300–400 m), and a barite mineralisation zone (15 m × 80 m) with massive to laminated veins and open-space fillings. Mineralogical studies confirmed high-purity barite (BaO 55–57 wt%, SO_3 28–34 wt%, SrO 1–3 wt%, minor PbO ≈ 2 wt%) with coarse, orthorhombic, euhedral to subhedral crystals, alongside gangue minerals like quartz, calcite, and minor sulfides. XRD analysis indicates barite comprises 84–99 vol.% of the deposit, with accessory quartz, gaspeite, and

todorokite. The deposit is a fault-controlled hydrothermal vein system, with mineralization facilitated by fracturing in Fe-Mg-rich andesitic rocks, creating fluid pathways and sulfate reduction. The barite mineralization of the Khargoshkan deposit is like volcanic-arc barite deposits in the Chenarvardeh NW Iranian Plate, where NW-SE structurally controlled barite deposited with Manganese (Mn), calcite (Ca), malachite and galena (PbO) as gangue mineral hosted in Eocene intermediate volcanic rocks. Future exploration should focus on fault zones within silicified and chloritized andesitic-dacitic sequences. The barite veins, associated with minor sulfides, may serve as a near-surface indicator for deeper copper-gold (Cu-Au) porphyry systems, it has implications in other region with similar geological settings. This research enhances the understanding of hydrothermal barite potential in the RasKoh arc.

Keywords: Khargoshkan barite deposit; RasKoh arc; Hydrothermal mineralization; Barite veins; Tethyan tectonic domain

Exploration and Geochemical Patterns of the Tuzgi Alkalic Porphyry Cu-Au Prospect, Southwestern Chagai Magmatic Arc, Balochistan, Pakistan

Fida Murad[1], Inayat Ullah[1,2*], Ahmed Shah Kakar[3], Abdul Ghaffar[3], Mei-Fu Zhou[2]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Quetta 87550, Pakistan; [2]State Key Laboratory for Critical Mineral Research and Exploration, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China; [3]National Resources Pvt. Limited, Karachi 75500, Pakistan

[*]Email: inayat.cem@um.uob.edu.pk

The Tuzgi alkalic porphyry (Cu-Au) prospect, located in the southwestern part of the Chagai magmatic arc in Balochistan, Pakistan, was explored through integrated geological, geophysical (including IP and ground magnetic surveys), and geochemical investigations. Lithological and hydrothermal alteration mapping, quartz vein assessments, and petrographic analyses define multiple phases of porphyry intrusions: (1) quartz alkali syenite porphyry (QASP), an early intermineral phase, (2) lamprophyre porphyry dikes (LPD), an intermineral stage, hornblende alkali syenite porphyry (HASP), late intermineral phase, and phyric alkali syenite porphyry (PASP) associated with post-mineralization. These magmatic phases intruded the alkali syenite units and the Paleocene Juzzak Formation. Hydrothermal alterations comprise potassic, phyllic, and propylitic zones, with surficial sulphide-rich mineralization. Notably, gold associated with chalcopyrite mineralization is primarily confined to the QASP and potassic alteration zones, whereas the LPD and biotite–magnetite potassic zones host native gold, chalcocite, and chalcopyrite. Geophysical anomalies of moderate to high intensity correlate with the main intrusive phases, delineating their lateral and vertical extents. Whole-rock major and trace element data suggest that the Tuzgi alkalic porphyry Cu–Au system predominantly comprises shoshonitic to alkalic intrusions, characterized by high total alkali contents ($Na_2O + K_2O$ = 5.86–11.31 wt%), elevated K_2O (1.55–7.56 wt%), high Sr/Y ratios (37.47–121.52), high La/Yb ratios (13.15–21.59), and variable Mg#

values [Mg# = Mg/(Mg + Fe^{2+}) × 100] ranging from 20.8 to 70.6. Trace element patterns show enrichment in large-ion lithophile elements (Ba, Rb, K, Th, U, Cs, Sr) and depletion in high-field-strength elements (Nb, Ti, Zr, P, Y), suggesting a subduction-related setting, likely above a subduction zone beneath thick continental crust. These geochemical patterns confirm that the magmatic evolution involved slab-derived fluids that metasomatized the mantle wedge, followed by partial melting and interaction with the lower crust. Crustal assimilation coupled with fractional crystallization produced ore-bearing adakitic magmas in the Tuzgi alkalic porphyry, similar to Tibetan Plateau porphyry deposits.

Keywords: Tuzgi Alkalic Porphyry (Cu-Au) Prospect; Exploration; Geochemistry; Adakite; Chagai Magmatic Arc

Petrology and Mineralization of Qila Abdullah Antimony (Sb) Deposits, Northwest Balochistan, Pakistan

Abdul Waris Khan[1,2], Inayat Ullah[1*], Muhammad Minhas[1], Shaheen Khan[1]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Pakistan;
[2] TMR Mining and Exploration Private Limited
[*]Email: inayat.cem@um.uob.edu.pk

Stibnite-hosted sedimentary rocks of the Khojak Formation in the Qila Abdullah are situated in the Flysch zone. This study examines the geological and mineralogical aspects of the deposit, including its lithological context, mineralization, and wall rock alteration. The deposit properties are analyzed in this study using recently obtained instrumental data (SEM-EDX and XRD). Sandstone interbedded with shale is the host rock. The deposit is fracture-controlled and fault-bounded, with varying thickness and distribution of stibnite veins. Alteration zones are characterized by silicification, calcification, and oxidation. Mineralogically, the ore rocks comprise stibnite, quartz, and rock-forming minerals with different crystalline and amorphous phases. The mineralogical compositions of the stibnite in the samples range from 45.4% to 89.2%. These high values of stibnite from the different types of ore samples of the Qila Abdullah deposit make it highly recommended for future mining and exploration.

Keywords: Hydrothermal; Stibnite; Silicification; Oxidized zones; Khojak

Integrated Remote Sensing and Geochemical Characterization of Cyprus-Type VMS Deposits in the Zhob Valley Ophiolites

Muhammad Ayoub Khan[1], Muhammad Shahab[2*], Fahad Alshehri[2]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan;
[2]Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, Geology and Geophysics Department, King Saud University, Riyadh 11451, Saudi Arabia
[*]Email: mshahab.c@ksu.edu.sa

The Naweoba and Bagh volcanogenic massive sulfide (VMS) deposits of the Zhob Valley ophiolitic belt, Pakistan, represent copper-rich mineralization hosted predominantly within mafic volcanic rocks of the Muslim Bagh and

Zhob ophiolites. This study integrates remote sensing, petrographic, and geochemical datasets to characterize and interpret the genesis of these deposits. Both deposits are characterized by well-developed stockwork, massive sulfide, and gossan zones, although their exposure and preservation vary spatially. The ore assemblage is dominated by pyrite and chalcopyrite, with subordinate sphalerite and pyrrhotite, whereas gangue minerals mainly comprise quartz, albite/plagioclase, chlorite, and sericite. Widespread chloritic and sericitic alteration within the basaltic host rocks indicates intense hydrothermal activity associated with VMS mineralization. Geochemical characteristics, particularly trace element and base-metal distributions, support a mafic volcanic affinity for the mineralized systems. The elevated Co/Ni ratios greater than 1 in pyrite suggest that hydrothermal processes played a dominant role in ore formation rather than purely sedimentary or diagenetic processes. Sulfur isotope compositions of pyrite and chalcopyrite further indicate that sulfur, and likely associated metals, were primarily derived from basaltic igneous rocks, with only limited contribution from seawater sulfate. Trace element variations in pyrite from the Naweoba deposit reveal a systematic vertical and paragenetic zonation. Stockwork-hosted pyrite is relatively enriched in Ni, Co, and Se, whereas pyrite from the massive sulfide zone shows enrichment in As, Zn, Pb, Mn, V, Ag, and Sb. These variations demonstrate that pyrite chemistry provides an effective vectoring tool for distinguishing deeper feeder-zone mineralization from shallower massive sulfide ores. The integrated geological, and geochemical signatures demonstrate that the Naweoba and Bagh deposits are consistent with Cyprus-type VMS deposits formed in an oceanic crustal environment related to ophiolite evolution. The Naweoba deposit, in particular, preserves geochemical and textural features comparable to modern seafloor hydrothermal systems, making it a fossil analogue of active submarine hydrothermal sulfide mineralization. This study highlights the importance of combining remote sensing-based alteration mapping with geochemical tracers for exploration and genetic interpretation of ophiolite-hosted VMS deposits in Pakistan and comparable tectonic settings worldwide.

Key Words: Cyprus-type VMS; Zhob Valley ophiolites; Naweoba–Bagh deposits; Hydrothermal alteration; Pyrite geochemistry

Mineralogical, Geochemical, and Gemological Characteristics of Katlang Topaz, Mardan, Pakistan

Adil Khan[1], Asghar Ali[2], Liaqat Ali[1*]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]Department of Geology, University of Peshawar, Peshawar 25120, Khyber Pakhtunkhwa, Pakistan

[*] Email: liaqat.nceg@uop.edu.pk

The Katlang pink topaz deposit, located at Ghundao Hill in District Mardan, Khyber Pakhtunkhwa, Pakistan, represents a geologically distinctive and gemologically important occurrence characterized by exceptional clarity and a characteristic pink coloration. This study investigates the origin, mineralogical

characteristics, geochemical composition, and gemological properties of Katlang topaz using an integrated analytical approach that includes petrography, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX), inductively coupled plasma mass spectrometry (ICP-MS), Fourier transform infrared spectroscopy (FTIR), and comparison with major topaz deposits worldwide. Petrographic observations show that topaz occurs within a calcite-rich foliated metamorphic host rock composed of muscovite and elongate quartz and is associated with quartz-calcite veins containing epidote and euhedral topaz crystals. Deformation features, including undulose extinction in quartz and polysynthetic twinning in calcite, indicate a two-stage geological evolution involving regional metamorphism followed by brittle deformation and later hydrothermal mineralization. SEM-EDX analysis reveals subhedral to euhedral crystals with low fluorine levels (2.58–5.75 wt%), confirming hydroxyl-dominant crystallization in a hydrous, low-F hydrothermal environment. The association with calcite and trace elements Cu, Zn, and Ti further validates a carbonate-buffered metasomatic origin within structurally controlled vein systems. ICP-MS analysis indicated pink topaz is significantly enriched in chromophores like Cr (avg. 37.5 ppm) and Mn (avg. 30.8 ppm), alongside elevated REEs and HFSEs (Nb, Ta), compared to colorless varieties. These geochemical signatures confirm that the pink coloration is driven by more evolved, metal-rich hydrothermal fluids and late-stage fractionation during crystallization. FTIR spectra confirm Katlang topaz as a well-ordered silicate lattice characterized by O-H stretching (4500–3500 cm^{-1}) and Si-O vibrations (1000–800 cm^{-1}), with trace chromium substitution and inclusions mica, feldspar, validate the hydrous nature and unique geological origin of its pink hues. Gemological analyses indicate high transparency, low inclusion density, slightly elevated refractive indices (1.631-1.640), specific gravity values of 3.503-3.588, and weak ultraviolet fluorescence. Katlang topaz is distinguished by its high clarity, chromium-related pink coloration, and inferred low-temperature hydrothermal origin. Integrated analyses characterize Katlang topaz as a low-fluorine, hydroxyl-dominant variety formed through hydrothermal mineralization within carbonate-buffered vein systems. The resulting chromium-driven pink coloration and exceptional clarity highlight its geological rarity and superior aesthetic quality.

Keywords: Katlang pink topaz; Hydrothermal mineralization; Gemological characterization; Trace element geochemistry; SEM-EDX analysis

Nephrite Deposits of the Ambar Area, District Mohmand, Khyber Pakhtunkhwa: Their Economic Value and Need for Modern Mechanized Mining and Processing

Muhammad Noman Khan[1,2*], Asghar Ali[2], Naveed Khan[4], Abdullah[2,3]

[1]Directorate General of Mines and Minerals, Peshawar, KP, Pakistan; [2]Dep. of Geology, University of Peshawar, Peshawar 25120, KP, Pakistan; [3] Geological Survey of Pakistan; [4]Government Gems and Jewellery Training Centre, Peshawar

[*] Email: noman.1627ma@gmail.com

Nephrite, a monomineralic rock, has been globally valued due to their use for ornamentation purpose since the history of mankind. Enormous deposits of nephrite or tremolite jade occur in the northern parts of the province of Khyber Pakhtunkhwa. Geologically, these deposits generally exist along the Main Mantle Thrust (MMT) – a tectonic boundary showing the suture zone of the Indian and Eurasian plates. A detailed study was undertaken on the Nephrite deposits of Ambar area located in the district Mohmand of Khyber Pakhtunkhwa. Their geological and gemological attributes revealed that these nephrites are essentially tremolite jade in composition and exhibit typical characteristics like color, hardness, toughness, specific gravity and refractive index as that of nephrite. Their bright green color and luster, high toughness and mineralogy make these nephrite deposits of higher economic value in the market. These nephrite deposits have been continuously mined since long and constitute the major supplies of the nephrite to the local needs and also exported abroad as well. Along with revenue generation for the government, they are also the main source of the livelihood for the local miners and their families. However, due to their occurrence in geologically highly complex mélange zone, their mining tends to be highly complicated. They are generally mined through uncontrolled blasting and unscientific manual methods. Resultantly, not only wastage of these commercially valuable nephrite deposits occurs but also a number of environmental impacts are inevitable besides safety concerns to the miners. Also, they are supplied to far-away markets in the raw form instead of finished end-products due to no nearby processing facilities which results in lesser economic benefits. Therefore, there is a dire need of opting modern mechanized mining in order to ensure the extraction of maximum useful amount of nephrite with minimum production of wastage and least environmental impacts. Also, the local processing, value addition and conversion into the end products need to be prioritized as it will lead to more employment opportunities, maximum revenue generation, production of export quality products and thus, bringing the wider socio-economic benefits to the country.

Keywords: Nephrite jade; Main Mantle Thrust; Gemological properties; Mohmand District; Sustainable mining

GeoHybridGNN for Next-Generation Porphyry Copper Targeting: Hybrid Remote Sensing, Graph Learning, and Geochemical Intelligence in the Western Chagai Belt, Pakistan

M. Atif Bilal[1*], Kateryna Hlyniana[3], Muhammad Pervez Akhter[4], Yongzhi Wang[1,2]

[1]College of Geoexploration Science and Technology, Jilin University, Changchun 130061, China; [2]Institute of Integrated Information for Mineral Resources Prediction, Jilin University, Changchun 130061, China; [3]School of Mathematics, Jilin University, Changchun 130061, China; [4]Computer Science Department, National University of Modern Languages, Faisalabad 38000, Pakistan

[*]Email: bilal6517@mails.jlu.edu.cn

Porphyry copper exploration increasingly requires intelligent spatial frameworks capable of integrating remote sensing, geological structure, lithology, and

geochemical evidence within a unified prospectivity model. In the Western Chagai Belt of Pakistan, major copper-gold (Cu-Au) systems occur in a structurally complex arc environment where mineralization is controlled by intrusive activity, fault corridors, hydrothermal alteration, and geochemical enrichment. This creates a need for advanced prospectivity models capable of integrating multi-source geological evidence into spatially coherent exploration targets. This study presents GeoHybridGNN, a hybrid deep learning framework designed for next-generation porphyry copper prospectivity mapping. The approach combines a CNN-based raster-patch encoder with a GraphSAGE-based graph learning model. Remote-sensing-derived hydrothermal alteration predictors, Cu geochemical information, distance-to-fault data, and lithology-based node attributes were integrated on a common spatial grid. The CNN branch captures local raster-patch patterns related to alteration and surface expression, while the graph branch aggregates geological and raster-derived node information through spatial neighborhood learning. The results show that GeoHybridGNN generates prospectivity maps that are spatially coherent and consistent with the main mineralized corridor of the Western Chagai Belt. Compared with tested graph-based models, the hybrid framework improves target organization and produces more interpretable exploration patterns. Cu geochemical integration has limited effect on global discrimination but provides modest local sharpening in selected target zones, suggesting its value as a refinement layer rather than a dominant regional predictor. This work demonstrates how hybrid remote sensing, graph learning, and geochemical intelligence can support uncertainty aware mineral targeting in structurally complex and arid terrains. The framework provides a practical pathway toward AI-assisted mineral exploration screening and more transparent geological decision-making.

Keywords: Remote sensing; Porphyry Copper prospectivity; Graph neural networks; GeoHybridGNN; Geochemistry; Mineral targeting

Sustainable Mineral Value Chain is Essential to Enhance the Role of Mineral Resources in National Socio-Economic Development

Muhammad Zeeshan Ullah

Directorate General of Mines and Minerals, Peshawar, KP, Pakistan
Email: m.zeeshan@uop.edu.pk

Pakistan in general while Baluchistan and Khyber Pakhtunkhwa in particular possesses a variety of huge mineral resources. Their sustainable utilization can ensure a firm industrial base, enhance employment opportunities, increase foreign exchange reserves and thus pave the way for socio-economic development at large. However, these ambitions can be realized only by the categorization of mineral resources on the basis of their value and potential and existing economic, strategic and technological priorities. Thereafter, designing a comprehensive mineral policy for the entire minerals value chain is essential including upstream, midstream and downstream. Upstream includes exploration of mineral resources and extraction of mineral reserves; downstream is the

processing and refining of the minerals while downstream refers to manufacturing the end-products. Ignoring or underestimating any element leads to derailing of the outcomes of the mineral sector. Though functionalization of the mineral value chain takes time, its fruition brings a range of economic outputs in the long run. Pakistan has been focusing upstream of the minerals value chain. It has been mainly extracting the mineral resources and exporting the resources, which results in bringing the capital for the short term. In order to ensure the enhanced role of mineral resources in the economy to increase GDP and foreign exchange reserves, the categorization of minerals based on their value and potential and the implementation of policy for the whole mineral value chain is mandatory. Transparent, uniform regulatory regimes and socio-political stability complemented by policy framework for mineral value chain can compel both local and foreign investors to turn their capital towards the mineral sector owing to growing global needs for a variety of minerals. It will not only help in increasing foreign exchange reserves but it may improve the local industrial sector bridging the widening import-export gap.

Keywords: Mineral value chain; Mineral policy; Resource categorization; Sustainable mining; Pakistan minerals sector

Research and Development in the Mineral Sector for the Sustainable Development of Mineral Resources of Khyber Pakhtunkhwa, Pakistan, and the Role of Academia

Muhammad Zeeshan Ullah

Directorate General of Mines and Minerals, Peshawar, KP, Pakistan
Email: m.zeeshan@uop.edu.pk

Every public and private organization focuses research and development (R&D) to enhance productivity and profitability, find new avenues and overcome emerging challenges. Due to lack of resources, organizations generally rely upon the academia for their expertise, advanced scientific knowledge and modern equipment. Like any other sector of economy, mineral sector consistently requires input from R&D due to emerging challenges of the increased demands by burgeoning population, need for sustainable supply chain and growing environmental concerns. However, generally in Pakistan and particularly in its province Khyber Pakhtunkhwa (KP), minimum focus is given to R&D. Due to its growing needs, one of the major gaps recognized in KP Minerals Development Policy 2014 was no formal or insufficient mechanism for R&D for mineral sector development. KP Minerals Development Policy 2022 and existing legal framework contains provisions for R&D that have rarely been implemented due to a number of administrative and institutional hurdles and insufficient capacity. However, academic institutions are also responsible for the sustainable development of natural resources keeping in view the current challenges and future needs. Its involvement in R&D can ensure the narrowing of target area to focus on the mineral prospects of optimum yield, devising sustainable mining plan and thereafter it can devise mid- and downstream strategies for the processing, value-addition and beneficiation to maximize the

yield and economic outputs. Therefore, Mines and Minerals Department and other stakeholders associated with the mineral sectors should make R&D as the integral part of their planning and operations by involving the academia. Also, the academia requires focusing on applied research and innovation. Academia needs to establish linkages with the stakeholders, promote integrity in their testing and reporting, make their publications and findings public, ensure their presence on digital media to get access to wider public. They may also hire the professionals involved in the sector of mines and minerals as adjunct faculty or in advisory capacity to have know-how of the real issues of the mineral sector. It will lead to foster R&D culture in the mineral sector and in turn it will improve the better utilization of mineral resources for the socio-economic development of the both province and the country.

Keywords: Mineral sector; Research and development (R&D); Academia–industry linkage; Sustainable mining; Khyber Pakhtunkhwa Pakistan

Constraints on Rare Earth Element (REE) Mobilization and Enrichment in Himalayan Alkaline–Carbonatite Systems, Pakistan

Mehboob ur Rashid[1,2*], Muhammad Jawad Zeb[2]

[1]Graduate School of Science and Engineering, Kagoshima University, Kagoshima 890-0065, Japan; [2]Geoscience Advance Research Labs, Geological Survey of Pakistan, Islamabad 44000, Pakistan

[*]Email: mehboobgeo89@gmail.com

Rare earth elements (REEs) hosted in alkaline–carbonatite systems represent critical resources for modern technologies; however, their mobilization and enrichment mechanisms remain incompletely understood, particularly in Himalayan tectonic settings. This study investigates the mineralogical and geochemical controls on REE enrichment within the carbonatite complexes of the Peshawar Plain Alkaline Igneous Province (PPAIP), northwestern Himalayas, Pakistan. Detailed field investigations, petrography and mineral chemistry analyses were conducted on major carbonatite bodies, in areas i.e., including Loe Shilman, Sillai Patti, Warsak, and Jambil. These intrusions occur along major fault-controlled zones within Proterozoic to Paleozoic metasedimentary sequences and are spatially associated with alkaline magmatism. Petrographic observations indicate calcite-dominated assemblages with significant contributions from apatite, biotite, and clinopyroxene, along with accessory REE-bearing phases such as monazite, pyrochlore, britholite, titanite, and bastnaesite. Whole-rock and mineral-scale geochemical data reveal pronounced enrichment of light REEs, with strong fractionation patterns indicative of magmatic differentiation processes. Textural and compositional variations in REE-bearing minerals suggest a two-stage enrichment mechanism: (1) primary magmatic concentration of REEs during carbonatite crystallization, and (2) secondary redistribution and localized enrichment driven by hydrothermal fluid activity. Evidence for fluid-mediated processes includes mineral alteration textures, compositional zoning and the presence of late-stage accessory phases. The geochemical signatures and regional geological

framework suggest that these carbonatite systems are linked to mantle-derived magmatism associated with extensional tectonics and possible plume-related activity. Subsequent fluid–rock interaction played a critical role in enhancing REE concentrations and controlling mineralization pathways. This study provides new insights into the coupled magmatic–hydrothermal processes governing REE enrichment in carbonatite systems. The results contribute to a better understanding of critical metal mineralization in rift-related settings and offer important implications for exploration strategies targeting REE resources in the Himalayan region and analogous global terrains.

Keywords: Rare earth elements; Carbonatite complexes; Magmatic–hydrothermal processes; Alkaline igneous province; REE mineralization; Peshawar Plain Alkaline Igneous Province

Exploration and Extraction of Rare Earth Elements from Coal in the Hangu Formation, Dawli Area, Pakistan

Ihtisham Ullah[1*], Liaqat Ali[1], Saleem Khan[1,2], Shah Fahad Alam[1]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]School of Energy Resources, China University of Geosciences, Beijing 100083, China

[*]Email: ihtishamk2018@gmail.com

This study examines the possibility of extracting rare earth elements (REEs) from coal samples acquired from the Hangu Formation in Dawli region of District Orakzai, Khyber Pakhtunkhwa (KP), Pakistan. A variety of advanced analytical techniques, such as proximate analysis, froth flotation, geochemical analysis (Atomic Absorption Spectroscopy and Inductively Coupled Plasma Mass-spectrometry (ICP-MS)), and mineralogical assessment using X-Ray Diffraction (XRD), Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM-EDS), were utilized in order to evaluate the geochemical composition, mineralogy, the coal's quality and the possibility of extracting the REEs. The gross calorific value (GCV) of the coal was determined to be 6400 BTU/lb, while proximate analysis indicated sulfur and ash contents of 1.8% and 24.5%, respectively. The coal samples underwent froth flotation process, which substantially improved the quality of the coal by enhancing its fixed carbon content by 12% while reducing its sulfur and ash content by 17% and 15%, respectively. Neodymium (Nd), Yttrium (Y), Cerium (Ce), and Samarium (Sm) are some of the most significant rare earth elements (REEs) found in the coal, according to the geochemical analysis. A specific concentration of these elements in the current coal was observed to be 0.015 and 0.030 for yttrium (Y) and cerium, respectively, and 0.022 and 0.007 for neodymium (Nd) and samarium (Sm). The results show that the coal samples have a relatively low enrichment of rare earth elements (REEs), having cerium as the highest concentration, followed by neodymium and yttrium. Through the flotation process, these percentages were further concentrated, and resulting in increased percentages of light REEs (LREE). The statistical assessments and results demonstrated that the ash content decreased significantly during flotation and

that the gross calorific value of flotation increased significantly, both of which indicated a substantial improvement in the quality coal quality. The results indicate that the coal of the Hangu Formation is enriched in important rare earth elements (REEs), and has large commercial importance with high energy potential. The advancement of technology, such as electronics, sustainable energy systems, and applications in the military, depending on these REEs. The region's strategic importance and ability to promote Pakistan's overall economic and technological growth are emphasized by the total potential for energy production and REE extractions.

Keywords: Rare Earth Elements (REEs); Hangu Formation; Froth flotation; Coal geochemistry; ICP-MS analysis

Geochemical Characterization and Life Cycle Assessment of Rare Earth Element Recovery from the Coal of South Baluchistan

Aneeza Munir[1]*, Muhammad Farooq Ahmed[1], Saif Ur Rehman[2]

[1]Geological Engineering Department, University of Engineering and Technology Lahore, Pakistan; [2]Institute of Geology, University of the Punjab, Lahore, Pakistan

[*]Email: niamatnkz@gmail.com; dr.rahib@gcu.edu.pk

The coal reserves of South Baluchistan, which are mainly lignite to sub-bituminous in grade, pose a twofold challenge: the deposition of coal waste as an environmental liability and the extraction of rare earth elements (REEs). This study combines the geochemical speciation with the life cycle assessment (LCA) to create a rank-sensitive, sustainable extraction framework to apply to this resource. Geochemical digestion and sequential leaching were used to characterize coal and coal waste samples of the main coal deposits (i.e., Chamalang, Duki, Mach and Kingri coal deposits). Geochemical data show rank-dependent REE distribution i.e., lower-rank lignites are organically-bound, middle-to-heavy (MREE/HREE) enriched (to 320 ppm total REEs, La/Lu ratio <5), and sub-bituminous coals are mixed organic-inorganic (clay-hosted) with light REE (LREE) preponderance. Characterization of coal ensures that REE increases 3-5-fold during combustion, which is mainly in the aluminosilicate minerals and phosphate phases. The findings of the paper compared three hydrometallurgical conditions under LCA, direct mild acid leaching (0.51 M HCl, ambient), thermal pretreatment (600 C decarboxylation) and acid leaching, alkali fusion (NaOH, 300 C). Direct leaching exhibits the lowest global warming potential (GWP = 2.8 kg CO_2-eq/kg coal waste) but recovers only 42% of the clay-hosted REEs. Alkali fusion achieves more than 85% REE recovery; however, it increases the GWP nearly fivefold (14.1 kg CO_2-eq/kg coal waste). Thermal pretreatment provides the most balanced option, yielding 68% REE recovery with a moderate GWP (6.5 kg CO_2-eq/kg coal waste) while consuming approximately 40% less acid compared to direct leaching. More importantly, the natural content of South Baluchistan sub-bituminous coals (812 wt.%) of calcium carbonate burns up 0.6 tons of acid per ton of coal wastes factor not included in the global models.

Keywords: South Baluchistan coal; Rare earth elements; Coal waste; Life cycle assessment; Hydrometallurgical extraction

Geological and Mineral Prospect Mapping of the Salt Range Area in Punjab Using Remote Sensing Tools

Aneeza Munir[1*], Muhammad Farooq Ahmed[2], Saif Ur Rehman[3]

[1]University of Engineering and Technology Lahore, Pakistan;
[2]Geological Engineering Department, University of Engineering and Technology Lahore, Pakistan; [3]Institute of Geology, University of the Punjab, Lahore, Pakistan
[*]Email: aneezamunir004@gmail.com

Pakistan hosts substantial industrial scale rocks and minerals resources, widely distributed across diverse geological provinces. The southern boundary of the hydrocarbon-rich Potwar Basin, also known as the Salt Range Thrust (SRT), contains some of the most significant geological and paleontological sites in Pakistan. This region is characterized by unique lithology, stratigraphy, and a wide spectrum of mineral deposits, including extensive high-purity salt reserves (~98%). However, due to its large spatial extent, rough terrain and remote location, most of its areas are unexplored. Recent advancements in satellite-based remote sensing and geospatial techniques have demonstrated their efficacy in exploring remote areas for natural resources. Particularly, rugged terrains on regional scale can be explored through remote sensing technology. Satellite remote sensing imagery is widely used for mapping economically important minerals and lithological units. This study applies advanced remote sensing and geospatial techniques to delineate lithological units and identify potential mineralized zones. ASTER sensor data, particularly its VNIR and SWIR bands, provide strong capability for lithological and mineral mapping in the Salt Range. Spectral reflectance of known minerals is used to classify imagery through techniques such as PCA, MNF, Decorrelation Stretching, and Band Ratioing. Spectral signatures of known minerals and rock units were used to classify and interpret ASTER imagery, enabling the identification of key mineral occurrences such as bauxite, bentonite, halite, fireclay, laterite, iron ore, antimony, celestite, copper, limestone, dolomite, Sulphur, gypsum, anhydrite, bituminous to sub-bituminous coal, and numerous other minerals. These techniques are extensively utilized in various industrial applications. The detected alteration zones were cross validated with known mining sites to ensure geological consistency. A final composite anomaly distribution map was generated by integrating lithological information provides a synthesized view of the region's mineralization potential. The results demonstrate that remote sensing offers a cost-effective technique for mineral prospecting particularly in inaccessible and geomorphologically complex terrain like Salt Range region. Additionally, detailed information on lithology and stratigraphy derived from this approach may lead to the discovery of new mineral deposits and support advancements in the hydrocarbon industry.

Keywords: Salt Range Thrust; Remote sensing; Lithological mapping; Mineral exploration; ASTER imagery

Integrated Remote Sensing and Structural Analysis for Mapping Mineralized Zones in the Nisai Region, Balochistan

Aneeza Munir[1*], Muhammad Farooq Ahmed[1], Saif Ur Rehman[2], Anas Bin Shah[1]

[1]Mineral Testing Laboratory, Mineral Development Department, Khyber Pakhtunkhwa, Pakistan; [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [3]Directorate General of Mines and Minerals, Peshawar, KP; [4]Government Gems and Jewellery Training Centre, Hayatabad, Peshawar, Pakistan

[*]Email: aneezamunir004@gmail.com

This research focuses on the remote sensing-based exploration of mineralization zones lying within the thrusted sheets of ophiolites in the younger sediments of Pishin Basin, in the vicinity of Nisai Village of the Pishin Belt, Balochistan. This region, despite its considerable geological potential within the Tethyan metallogenic belt, remains largely underexplored. Utilizing multispectral satellite datasets, including Landsat 8 OLI and ASTER, we applied an advanced suite of digital-image processing techniques. These techniques encompass Band Ratios (BR), Principal Component Analysis (PCA), Minimum Noise Fraction (MNF) transformation, Decorrelation Stretch (DS), and convolutional filtering, which collectively facilitate the precise delineation of magmatic zones, critical indicators of mineral deposits. This approach is particularly adept at isolating spectral signatures associated with iron oxides, chromite, carbonates, asbestos, soapstone and silicified zones, each providing essential insights into the underlying hydrothermal activity in the region. This analysis was further refined by incorporating anomaly-specific RGB composites which facilitated the identification and mapping of key alteration zones. In addition to this spectral analysis, structural lineament mapping utilizing directional filtering and DEM-based methods demonstrated a strong spatial correlation between fault systems and alteration zones. This observation underscores the pivotal role of tectonic structures in directing hydrothermal fluid flow and influencing mineral deposition patterns. Data interpretation findings were rigorously validated through fieldwork and cross-referenced with established mineral occurrences within the Chagai–Pishin metallogenic domain, thereby confirming the reliability of our remote sensing results. The conclusion of this study is an integrated mineral prospectivity map that synthesizes alteration signatures, structural trends, and spatial anomalies into a cohesive exploration framework. This map not only identifies previously unrecognized high-priority targets but also serves as a practical tool for guiding future field investigations, geochemical sampling, and drilling programs. Ultimately, this study demonstrates the powerful synergy of combining remote sensing data with structural geology to unravel complex mineral systems, providing a robust and actionable roadmap for advancing sustainable resource development in the Nisai region of Balochistan.

Keywords: Mineralization zone; Hydrothermal alteration; Remote sensing; Lineament analysis; Multispectral image processing; Pishin Belt

Integrated Remote Sensing and Multispectral Analysis for Delineating Mineralization Zones in the Waziristan Ophiolite Complex, Pakistan

Darmana Maqbool*, Mohib Ur Rehman

Department of Earth Sciences, COMSATS University Islamabad, Abbottabad Campus, Pakistan

Email: darmanamaqbool0000@gmail.com

In mineral exploration, remote sensing (RS) techniques are practical and economical. In broader geographic areas, metallogenic provinces, belts, sides, and mineral guides can be identified using RS data. The Boya Razmak research region in North Waziristan contains a noteworthy ophiolite sequence. Satellite data was helpful in this investigation because of the inaccessibility, exposed Waziristan ophiolite, sedimentary igneous lithologies, and rough terrain with little vegetation. Oceanic lithosphere segments known as ophiolites, which are obducted onto the continental crust, provide information about processes like asthenospheric upwelling, mantle melting, continental rifting, and oceanic lithosphere cooling. The study aims to assess the potential of three multispectral satellite imagery Landsat-8 OLI, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, and Sentinel-2 for mapping alteration zones, gossan, iron oxide, and clay minerals under low vegetation cover in North Waziristan (Boya Razmak) and the surrounding area. In order to map ultramafic terrain visible, short and thermal infrared raw bands were acquired and analyzed using satellite image interpretation techniques, such as false and true color composites. Spectral signatures from satellite imagery were used to differentiate between rock units and alteration zones, and different techniques, such as band ratios and band combinations can be helpful in this approach. Results shows that large-scale mineral discovery can benefit from the combined use of numerous satellite images with different spatial and spectral resolutions. Notably, ASTER data has demonstrated exceptional efficiency, producing remarkably noticeable outcomes in identifying supergene copper mineralization. According to the findings, the technique is promising for identifying alteration zones and could be applied to the exploration of iron, manganese, copper, and chromite in comparable areas elsewhere.

Keywords: Remote sensing; Ophiolite complex; Mineral exploration; Satellite imagery; Alteration zone

Katlang Topaz: A Unique Geographic Indicator of Himalayan Hydrothermal Mineralization, Geochemical Signatures, Formation Mechanisms, and Economic Potential

Izaz Aziz[1]*, Israr ud Din[2], Shahid Ullah[1], Wajid Khan[1], Muhammad Noman Khan[3], Naveed Khan[4]

[1]Mineral Testing Laboratory, Mineral Development Deptt., Khyber Pakhtunkhwa, Pakistan; [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar, KP; [3]Directorate General of Mines and Minerals, Peshawar, KP; [4]Government Gems and Jewellery Training Centre, Hayatabad, Peshawar, Pakistan
[*]Email: azykhan172@gmail.com

Katlang Topaz represents a globally unique occurrence of naturally pink topaz $Al_2SiO_4(F,OH)_2$ from Ghundao Hill near Katlang, District Mardan, northern Pakistan. This study presents comprehensive mineralogical, geochemical, and genetic characterization of this exceptional gemstone variety, integrating recent advances in topaz crystal chemistry and Himalayan tectonics. Genetically, Katlang Topaz occurs within hydrothermal calcite-quartz veins cross-cutting Silurian-Devonian recrystallized limestones of the Lower Swat-Buner Schistose Group. Unlike most pegmatite-hosted topaz globally, Katlang topaz formed at ~230°C from saline fluids during the Eocene India-Eurasia collision. It crystallized in tension gashes along fold axes, indicating syn-tectonic fluid flow. Its crystal chemistry is unique, being OH-dominant with OH/(OH+F) > 0.6, unlike typical F-dominant topaz worldwide. Trace element analysis reveals diagnostic Cr_2O_3 (0.01-0.03 wt.%), producing the prized cyclamen pink color, with subordinate V_2O_3 (0.03-0.08 wt.%) and negligible Fe or Mn. This signature reflects Cr mobilized from regional ultramafic rocks during metamorphic devolatilization. This unique Cr-V-rich, F-poor signature serves as a reliable geographic indicator, supporting certification protocols for international gemstone trade. The Advanced Raman spectroscopy and FTIR analysis confirm the OH-rich nature through OH-stretching bands at 3650-3680 cm^{-1}, while UV-Vis spectroscopy reveals diagnostic Cr^{3+} absorption at 682 nm. Photoluminescence studies show Cr^{3+} emission peaks from octahedral Al sites, confirming chromium causes the color. The morphological and physical properties show that the crystals are prismatic along the c-axis, with well-developed {110} and {120} prism faces. Size distribution ranges from <5 mm to exceptional specimens >75 mm, with refractive indices (1.630-1.642) and specific gravity (3.51-3.53). Hardness (8 Mohs) and perfect (001) cleavage align with topaz standards, while moderate pleochroism ranges from pale pink to violet. The fluid inclusion studies suggest two-phase (L+V) reveals homogenization temperatures of 180-280°C and salinities of 8-15 wt.% NaCl equiv., indicating formation from moderate-temperature, saline hydrothermal fluids. Stable isotope data ($\delta^{18}O$, δD) suggest fluid sources derived from metamorphic dehydration of carbonate-bearing sequences during regional metamorphism. With estimated reserves of ~9 Mct and 20,000-30,000 ct annual production, Katlang Topaz is Pakistan's top gemstone after the Swat emerald.

Its 100% natural, untreated color gives a key edge in the market for authentic gems. This study shows hydrothermal topaz can form in metamorphic terranes, moving beyond pegmatite-centric models. Katlang topaz reveals fluid–rock interaction during continental collision, informing critical mineral exploration across the Himalaya. The synthesis of OH-rich topaz analogues and blockchain provenance tracking for ethical sourcing. Linking these results with regional tectonics and metallogeny will improve exploration for similar deposits throughout the Himalayan orogen.

Keywords: Katlang topaz; Himalayan mineralization; OH-rich topaz; Chromium coloration; Geographic indicator; Hydrothermal gemstone

Structural and Stratigraphic Controls on Polymetallic (Pb, Zn, Cu, Sb) Mineralization along the Reshun Fault System, Upper Chitral, Pakistan: Implications for Ore Genesis and Resource Potential

Shahid Ullah[1*], M. Asif Ali Shah[1], Wajid Khan[1], Izaz Aziz[1], S. Irfan Ullah Hashmi[2]

[1]Mineral Testing Laboratory, Mineral Development Departmen KP, Pakistan;
[2]Energy and Power Department KP, Pakistan
[*]Email: shahid.ullah@kpminerals.gov.pk

The research integrates field mapping, structural analysis, mineralogical and geochemical signatures of nineteen (19) representative mineralized samples to evaluate ore genesis and resource potential. Results indicate significant polymetallic mineralization hosted within sheared metasedimentary rocks of the Darkot Group, with exceptionally high metal concentrations reaching ~27.7 wt.% Zn and ~17.9 wt.% Pb, alongside anomalous Sb and Cu enrichments. Mineralogical analyses confirm the dominance of galena, sphalerite, chalcopyrite, and pyrite, consistent with a hydrothermal sulfide assemblage comparable to Mississippi Valley-Type (MVT-like) mineralization. Structural data demonstrate that mineralization is primarily controlled by the Reshun Fault and associated fracture networks, which acted as conduits for metal-bearing hydrothermal fluids. Ore occurs in fault-hosted veins, veinlets, and fractured zones, while no consistent stratigraphic control or preferential host horizon was identified. These findings support an orogenic hydrothermal model in which fault architecture played the principal role in ore localization. The unusually high Pb–Zn grades and the presence of strategic metals such as antimony highlight significant economic potential for the Chitral Hindukush metallogenic belt. This study emphasizes the exploration significance of structurally controlled polymetallic systems along major fault corridors and supports continued drilling, geophysical surveys, and geochemical targeting along the Reshun Fault to delineate additional base-metal resources.

Keywords: Polymetallic mineralization; Reshun Fault; Pb–Zn ore deposits; Hydrothermal systems; Hindukush metallogenic belt

Preserving Himalayan Fieldwork: A Digital Tribute to Mohammad Khan

Khaista Rehman

NCEG, University of Peshawar, Peshawar. Pakistan
[*]Email: rehmannceg@uop.edu.pk

This digital archive celebrates Mohammad Khan, whose three decades of service (1973–2009+) as driver, guide, translator, and field assistant enabled countless geological expeditions across the western Himalayan syntaxis and adjacent mountain belts. His local knowledge of terrain, weather patterns, and remote access routes directly contributed to the success of numerous tectonic, stratigraphic, and geophysical studies conducted by international teams from Dartmouth College and Oregon State University, USA, as well as local teams from the National Centre of Excellence in Geology (NCEG), the Department of Geology at the University of Peshawar, and other government organizations in Pakistan. The archive is built from high-resolution scans of original field photographs, each captioned to provide geological context including rock types (e.g., schists, gneisses, limestones, and granites), deformation features (folds, faults, and shear zones), and geophysical instrumentation (gravity meters, GPS units, and magnetometer). Through thematic organization, this digital tribute documents not only the spectacular Himalayan landscape but also the essential human partnerships that underpin field data collection in extreme environments. The project offers a replicable model for honouring non-academic field staff—often invisible in final publications—who are integral to research success. It serves as institutional memory for NCEG and an inspiration for similar preservation efforts across geoscience departments worldwide.

Keywords: Digital archive; Himalayan geology; Field expeditions; Geological heritage

Theme 2: Structural Geology & Tectonics

Tectonics, Structural Controls, and Evolution of the Makran Accretionary System Revisited

Pedro A. Restrepo-Pace[1*], Salik Javed[1,2,3], Benazeer Iqbal[1]

[1]DeGolyer and MacNaughton, 5001 Spring Valley Road, Suite 800 East, Dallas, Texas 75244, USA; [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [3]GIS and Space Applications in Geosciences (GSAG), National Centre of GIS and Space Applications (NCGSA), Institute of Space Technology, Islamabad, Pakistan
[*]Email: prestrepo@demac.com

The Makran Accretionary System has long been the focus of regional geological investigations, yet integrated geometric and kinematic assessments remain limited. This extensive tectonic wedge, characterized by its low taper, is constructed through the convergence of the Arabian Plate from the south and the

Helmand Block to the north. Its overall geometry is constrained by subsurface datasets including earthquake foci, gravity modeling, seismic profiles, and surface geological observations. Kinematic evolution is interpreted as being driven by foredeep development during Late Cretaceous-Paleocene time, expressed through a progressive break-forward thrust system, subsequently refolded and modified by underplating processes. The deeper sedimentary sequences above the subducting oceanic slab remain loosely constrained, reflecting uncertainties in the structural configuration of the internal wedge. In this study, we synthesize available datasets to refine the geometric framework of the Makran system and present a structural forward model extending from the Balochistan-Kharan Forearc Basin to the Murray Ridge. This model illustrates the multistage evolution of the accretionary prism and highlights unresolved aspects of tectonic development, including the basement signature inferred from exposed volcanics and intrusive in the hinterland. Finally, the Makran system is contextualized within global accretionary systems, offering comparative insights into wedge dynamics and tectonic processes.

Keywords: Makran Accretionary System; Structural evolution; Underplating processes; Baluchistan Structural evolution; Tectonic kinematics

Late Cretaceous Alkaline Intrusions of the Sulaiman Fold-Thrust Belt: Emplacement Mechanism and Tectonic Evolution

Muhammad Panezai[1], M. Ishaq Kakar[1], Rahat Ullah[2*], M. Qasim Jan[3,4]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan; [2]Geological Survey of Pakistan, Quetta/Islamabad, Pakistan; [3]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [4]China-Pakistan Joint Research Centre on Earth Sciences, Islamabad, Pakistan

[*]Email: rahatullah238@gmail.com

Late Cretaceous alkaline sheet intrusions in the Sulaiman Fold–Thrust Belt are dominated by sills, with minor dykes and occasional laccoliths emplaced in Mesozoic sedimentary rocks along the NW Indian Plate margin. Their emplacement geometries (fingers, bridges, splays, and lobes) indicate mixed brittle and ductile emplacement controlled by host-rock lithology and rheology. Geochemical and geochronological data link them to pre-Deccan Réunion plume activity (~70 Ma), consistent with hotspot magmatism across the Indian Plate. Field observations show symmetrical laccoliths and dyke-fed sills, indicating shallow, incremental emplacement of magma at low-moderate magma volumes. Tectonically, the region records three structural regimes: (1) NE–SW thrusting and folding during Cretaceous–Eocene ophiolite obduction, (2) NW–SE strike-slip deformation forming large scale boudins and sigma porphyroclasts, and (3) N– S structures related to crustal rotation and E–W shortening. These intrusions cut hydrocarbon bearing sedimentary units, including the Triassic Gwal and Wulgai formations. It is likely that fracturing enhanced hydrocarbon migration and trapping, while thermal effects may have locally over-matured source rocks.

Keywords: Alkaline magmatism; Réunion hotspot; Sill-form intrusions; Sulaiman FTB

Thick-Skinned Deformation Driven by Jurassic Fault Inversion in the Frontal Folds of the Southern Kirthar Fold Belt, Sindh, Pakistan

Aijaz Ali Halepoto[1*], Surriya Bibi Ahmedani[1,2], Muhammad Hassan Agheem[1], Shabeer Ahmed[1,3], Asghar A. A. D. Hakro[1]

[1]Centre for Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan; [2]Government Zubeda Girls College, Hyderabad, College Education Department, Government of Sindh, Pakistan; [3]Oil & Gas Development Company Ltd, Islamabad, Pakistan

[*]Email: aijaz.halepoto@usindh.edu.pk

The Southern Kirthar Fold Belt (SKFB) represents the southernmost continuation of the regional Himalayan-Suleiman-Kirthar orogenic system. This orogenic belt formed as a result of the oblique continent to continent impact amid the Eurasian and Indian Plates. The SKFB lies head-to-head to the Indian Plate's western transpressional edge, which is delineated by the Ornach Nal Chaman Fault System. To the east, the SKFB is bounded by the Sindh monocline. To the north, it transitions into the Kirthar Foredeep plus the Central Fold Belt of Kirthar. In the south, the western part of the SKFB passes into the Offshore SW-NE trending Murray Ridge, while its eastern segment is bounded by the Sindh monocline along the Karachi Keenjhar right lateral Boundary Fault (KKBF). The present transpressional regime was preceded by multiple rifting events during the Jurassic and Cretaceous periods. The SKFB has traditionally been interpreted as a thin-skinned imbricate fan system, developed above a detachment located within the shales of the Early Cretaceous Sembar and Goru Formations at depths of 3-4 Km below sea-level. However, the influence of Mesozoic extensional structures on the development of later contractional folds has received little attention. This study aims to re-interpret the frontal folds of the SKFB using a thick-skinned deformation template, which involves the inversion of pre-existing Jurassic extensional faults.Surface geological data and subsurface well data from different folds across the SKFB were utilized to construct balanced cross-sections. Initial attempts to balance the cross-section using a thin-skinned framework, placing the detachment within the Early Cretaceous Sembar and Goru shales, proved unsuccessful. Instead, a sub-vertical fault geometry beneath the folds was required to achieve balance, rather than a shallow sub-horizontal detachment with an emergent thrust. The sub-vertical fault geometry indicates the role of inverted extensional fault in fold development. These extensional faults interpreted to have formed within the Jurassic Chiltan Formation, which was deposited during early to middle Jurassic rifting of the Indian Plate from the Western Gondwanaland. The thick-skinned interpretation is further supported by analysis of shortening magnitude. Thin-skinned fold-thrust systems usually accommodate considerable horizontal shortening, whereas thick-skinned inversion structures accommodate significantly less. The folds analyzed in this study accommodated only 200 to 500 m of shortening, representing less than 10 % of the total tectonic shortening. Therefore, present study here supports a thick-skinned deformation model for

the SKFB, driven by the inversion of extensional faults (Jurassic) during the collision of the Indian Plate (Cenozoic) with the Eurasia.

Keywords: Southern Kirthar Fold Belt; Thick-skinned deformation; Fault inversion tectonics; Jurassic extensional faults; Himalayan–Suleiman–Kirthar orogeny; Balanced cross-sections

Deformation History and Tectonic Significance of Mesoscopic Structures along the Main Boundary Thrust, Northwestern Indian Plate Margin

Abdullah[1*], Sajjad Ahmad[2], Gohar Rehman[2], Rahat Ullah[1], M. Noman Khan[3]

[1]Geological Survey of Pakistan, Quetta/Islamabad, Pakistan;
[2]Department of Geology, University of Peshawar, Peshawar 25120, KP;
[3]Directorate General of Mines and Minerals, Peshawar, KP, Pakistan
[*]Email: abdullah7329@uop.edu.pk

The study aims to analyze and interpret the tectonic evolution of mesoscopic structures (folds and faults) within the hanging wall of the Main Boundary Thrust (MBT) in the Orakzai District, Khyber Pakhtunkhwa, Pakistan. Structural data were analyzed using lower-hemisphere stereographic projections to identify deformation events associated with the MBT. Analysis of axial plane orientations shows that most folds and faults are overturned toward the southwest and southeast, with minor occurrences of northward overturning. These structural patterns suggest that the mesoscopic fabric is consistent with both regional and local transport directions along the MBT hanging wall. In addition, some mesoscopic faults record east–west compressional regimes, verging either eastward or westward. These structural features are consistent with east–west tectonic stresses related to the counterclockwise rotation of the Indian Plate and associated syntaxial bending, expressed regionally as the Hazara–Kashmir Syntaxis. They may also reflect westward-directed collision processes and eastward obduction of the Afghan Block onto the Indian Plate. Overall, the results indicate multiple phases of deformation in the study area. The earliest phase is characterized by north–south compression linked to the Indo–Eurasian collision, followed by a later phase associated with counterclockwise rotation of the Indian Plate and eastward obduction of ophiolitic complexes and the Afghan Block onto the Indian Plate.

Keywords: Main Boundary Thrust; Mesoscopic structures; Fold and fault analysis; Tectonic evolution; Hazara–Kashmir Syntaxis

Structural Deformation and Petrography of the Muzaffarabad to Nauseri Road Area, Hazara Kashmir Syntaxis, Azad Kashmir, Pakistan

Majid Farooq[1*], Muhammad Yasin Khan[2]

[1]Geological Survey of Pakistan, Islamabad, Pakistan; [2]Institute of Geology, University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan
[*]Email: majidfarooq415@yahoo.com

The study area is situated in the core region of the Hazara–Kashmir Syntaxis (HKS), Northwestern Himalayas, Pakistan, and lies within District Muzaffarabad, Azad Kashmir. Geographically, the project area is bounded by the Main Boundary Thrust (MBT) to the north and the Muzaffarabad Fault (MF) to the south. The lithostratigraphic succession exposed in the area ranges in age from Cambrian to Recent. The exposed rock units include, in ascending order, the Abbottabad Formation (Cambrian), Panjal Formation (Permian), Hangu Formation (Paleocene), Lockhart Limestone (Paleocene), Patala Formation (Paleocene), Margalla Hill Limestone (Eocene), Chorgali Formation (Eocene), Kuldana Formation (Eocene), Murree Formation (Miocene), and Recent alluvium. Structurally, the area is intensely deformed and exhibits a complex tectonic framework characterized by multiple generations of folds and faults. Major fold structures identified within the project area include the Chalpani Anticline, Patikka Syncline, Patikka Anticline, Panjgran Syncline, Panjgran Anticline, Devlian Anticline, Balgran Syncline, and Nauseri Anticline. Prominent fault systems exposed in the study area comprise the Yadgar Back Thrust, Ghori Back Thrust, Chalpani Fault, Devlian Fault, and the Main Boundary Thrust, reflecting a strong compressional tectonic regime associated with Himalayan orogenesis. The stratigraphic facing of rock units has been determined based on the recognition of primary sedimentary structures observed in the field. Detailed geological investigations were conducted to understand and document the structural architecture of the area, with particular emphasis on the identification and interpretation of structural features, petrological characteristics, and other diagnostic attributes of the Kuldana Formation and Murree Formation.

Keywords: Hazara–Kashmir Syntaxis; Himalayan tectonics; Structural geology; Stratigraphy; Kuldana Formation; Murree Formation

Theme 3: Engineering Geology, Geotechnical Engineering & Construction Materials

Assessment of Foundation Seepage Control Measures in an Embankment Dam Considering Alternative Approaches for Stratum Heterogeneity

Zaheer Muhammad Malik, Asma Azad*, Atiq Ur Rehman Tariq

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan

**Email: usmaazad143@gmail.com*

Embankment dam safety depends on reliable foundation seepage control to prevent internal erosion and piping failures. Conventional designs rely on homogeneous or simplified layered models, which often mask the influence of realistic geological heterogeneity on seepage predictions. While extensive parametric studies exist on cutoff walls and impervious blankets, their

performance under spatially variable, heterogeneous foundations remains inadequately quantified. In this study, two distinct heterogeneity representations are developed from 179 in-situ permeability tests: a layered single-pervious-zone model and a spatially detailed multi-zoned profile using the Closest Point Algorithm. Over 2,000 steady-state, 2D finite element simulations evaluated four broad configurations of partial cutoff walls, impervious blankets, and their combined systems. Results demonstrate that while total head dissipation is similar across models, exit gradients are highly sensitive to the heterogeneity representation. The detailed model predicted exit gradients 25–30% higher at the critical core-toe interface. An upstream impervious blanket provided robust control, reducing the critical gradient by approximately 75%. For combined systems, placing a cutoff upstream of the blanket maintained safe gradients, while placing the cutoff downstream risked significant gradient amplification. Consequently, for deep heterogeneous foundations without bedrock, a full-length upstream blanket paired with an upstream cutoff is recommended, with final safety verification requiring spatially resolved heterogeneity models to avoid non-conservative design.

Keywords: Embankment dams; Foundation seepage; Geological heterogeneity; Cutoff walls; Finite element modeling

Evaluating the Role of Texture Coefficient in Defining the Geotechnical Properties of Carbonate Rocks

Subhan Ullah[1,2*] Muhammad Sajid[3,4], Khalid Latif[1], Abdul Rahim Asif[1]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar , KP;
[2]Deptt. of Geology, University of Swat, KP, Pakistan;
[3]Department of Geology, University of Peshawar, Peshawar 25120, KP, Pakistan;
[4]Department of Geology, Abdul Wali Khan University Mardan, KP, Pakistan
[*]Email: subhanullah873@gmail.com

Understanding the microfabric of carbonate rocks is essential for evaluating their geotechnical properties. This study investigates the role of the Texture Coefficient (TC) in quantifying the microfabric and assessing its influence on the geotechnical properties of Upper Indus Basin carbonate rocks. A variety of carbonate rocks, including limestone, dedolomitized limestone, and dolostone, were investigated through petrographic observations and physical and automated tests. These tests included porosity, density, ultrasonic pulse velocity, unconfined compressive strength, Schmidt hammer rebound, and point load indices. The results show that TC values are generally higher in samples with a greater abundance of grains. However, regression analysis indicates a weak and inconsistent correlation between TC and the measured physical and mechanical properties. This is because TC make available a simplified measure of texture and does not fully account for important factors such as mineralogical composition, matrix type, and diagenetic alterations. This study emphasizes the need for a comprehensive approach that integrates TC with petrographic observations to better understand the geotechnical behavior of carbonate rocks.

Keywords: Carbonate rocks; Texture coefficient; Microfabric analysis; Geotechnical properties; Upper Indus Basin

Engineering and Geochemical Characterization of Hassan Khel Limestone for Cement and Construction Industries

Fazl Ullah[1*], Liaqat Ali[1], Abdul Rahim Asif[1], Izaz Aziz[2]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [2]Mineral Testing Laboratory, Mineral Development Department, KP, Pakistan

[*]Email: faizy4655@gmail.com

Limestone is a vital and economically significant raw material with widespread applications across the construction and chemical industries worldwide. The Hassan Khel region of the Peshawar Basin, Pakistan, hosts extensive limestone deposits spanning three distinct formations: the Samana Suk, Lockhart, and Darwaza. This study presents a comprehensive mineralogical, geochemical, and mechanical evaluation of these formations to assess their suitability for cement manufacturing, concrete production, road construction, and other industrial applications. Geochemically, the Hassan Khel limestone is characterized by notably high calcium oxide (CaO) content across most samples, with localized exceptions in the Lockhart and Darwaza formations. Silicon dioxide (SiO_2) concentrations are generally low, although selected samples exhibit elevated silica levels—though not sufficient to classify as argillaceous limestone. Aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3) remain within permissible limits for diverse industrial uses, while sodium oxide (Na_2O) and potassium oxide (K_2O) occur only in trace amounts, reflecting high purity. Magnesium oxide (MgO) occasionally shows minor elevated values at specific locations but remains broadly compliant with industry standards. Mineralogically, the limestone is predominantly composed of calcite with variable grain sizes, accompanied by minor quartz. Diagenetic features including iron leaching, micro-fractures, and stylolites are observed in several samples. A suite of mechanical tests—including unconfined compressive strength (UCS), unconfined tensile strength (UTS), Los Angeles abrasion, unit weight, specific gravity, bulk density, porosity, water absorption, and aggregate impact value—was conducted to evaluate performance in concrete, asphalt, and roadstone applications. The mechanical data compare favorably with relevant ASTM standards, with average properties falling within prescribed limits. Based on these integrated findings, limestone samples from the Hassan Khel formations are deemed suitable for a range of industrial applications. Notably, the Samana Suk Formation is specifically recommended as a high-quality raw material for cement manufacturing.

Keywords: Limestone characterization; Samana Suk Formation; Hassan Khel; Geochemistry; Mechanical properties; Cement raw material

Stability Assessment of Tunnel Using RMR and Q-System: A Case Study from Northern Pakistan

Muhammad Shoaib[1*], Muhammad Sajid[1,2]

[1]Department of Geology, University of Peshawar, Peshawar 25120, KP, Pakistan; [2]Department of Geology, Abdul Wali Khan University Mardan, KP, Pakistan
[*]Email: muhammadshoaib22@uop.edu.pk

This study examines the engineering geological characteristics of rock masses encountered along a hydropower headrace tunnel in the Swat region of northern Pakistan. The project area lies within the Mesozoic Kohistan Island Arc system in the igneous and meta-sedimentary sequences. Rock mass conditions and their implications for tunnel stability and support design are assessed using the Rock Mass Rating (RMR) and Rock Mass Quality (Q-system) classification methods. Field investigations were conducted through systematic scanline mapping to record key discontinuity features, including orientation, spacing, aperture, and surface roughness. Based on these data, the rock mass was classified as "Good" to "Fair" according to the RMR system, whereas the Q-system indicated conditions ranging from "Fair" to "Very Poor." The comparatively lower ratings obtained from the Q-system are primarily attributed to groundwater effects and the presence of unfavorable joint configurations. Petrographic studies indicate that quartzite and granodiorite are the principal lithologies along the tunnel alignment. Quartzite, characterized by a fine-grained texture and a high density of fractures, generally exhibits lower rock mass quality. In contrast, granodiorite, with its coarse-grained fabric, demonstrates relatively better mechanical competence. A site-specific empirical relationship between RMR and Q values was developed, yielding a coefficient of determination (R^2) of 0.53. This correlation was further evaluated against previously published models, leading to the formulation of a generalized regression equation that integrates the present dataset with existing case histories from varied geological settings. The findings highlight that combining empirical classification approaches improves the reliability of preliminary rock mass evaluation and support design for tunneling projects in complex island arc environments.

Keywords: Rock mass Characterization; Rock Mass Rating (RMR); Q-System; Kohistan Island Arc; Petrographic analysis; Tunnel stability

Evaluation of Engineering Properties of Carbonate Rock from Mughal Kot Section through Texture Coefficient

Fazl Ullah[1*], Muhammad Sajid[1], Amir Khan[1], Izaz Aziz[2]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]Mineral Testing Laboratory, Mineral Development Department, Khyber Pakhtunkhwa, Pakistan
[*]Email: faizy4655@gmail.com

Petrographic studies and mechanical investigations of carbonate rock in the vicinity of Mughal Kot section of the eastern Suleiman ranges in western Pakistan were carried out to assess their feasibility for geotechnical purposes.

Mughal Kot section comprises different lithologies including shale, sandstone, and carbonates. Carbonate rocks of Mughal Kot section can be texturally divided into mudstone, wackestone, packstone and grainstone. Mudstone and wackestone samples are studied in the current approach. Mud supported carbonates are highly composed of micrite and bioclast with no intraclasts and peliods. Few samples have a little amount of sparite. In order to describe a grain, measurement of rock texture, relative proportions of matrix (packing density) and grains, shape, orientation, and degree of grain interlocking have been developed known as Texture Coefficient (TC). The texture coefficient was measured by using software for detailed petrographic analysis. The TC reveals statistically major relations with strength of rock and other mechanical properties. For geotechnical purposes, physico-mechanical and aggregate properties including UCS, Los-Angeles abrasion, Water absorption, specific gravity and porosity representing various textural varieties were determined and correlated with texture coefficient. Depending on these statistical values and texture coefficient data a graphical comparison is made that indicates that mud supported carbonates show an inverse relationship between strength and texture coefficient (TC). It is further observed that fine-grained and mud supported show high strength than their counterparts. The results of geotechnical tests show that the studied carbonates are well within the permissible range to be used as aggregate for both concrete and asphalt works.

Keywords: Carbonate rocks; Texture coefficient; Petrography; Geotechnical properties; Mughal Kot section

Petrography and Geotechnical Properties of Malakand Granite, Northwestern Pakistan

Sajjad Ahmad[1*], M. Arif[2], Muhammad Sajid[2,3], Subhan Ullah[1,4], Abdul Rahim Asif[1]

[1] National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [2]Department of Geology, University of Peshawar, Peshawar, KP, Pakistan; [3]Department of Geology, Abdul Wali Khan University Mardan, KP, Pakistan; [4]Department of Geology, University of Swat, Khyber Pakhtunkhwa, Pakistan

[*]Email: sajjadahmadshagai@gmail.com

The engineering behavior of any rock mass is fundamentally a reflection of its internal fabric and mineral architecture. Four representative bulk rock samples from the Malakand Granite in northwestern Pakistan were investigated to evaluate their petrographic characteristics and physico-mechanical properties. Detailed petrographic examination enabled the classification of the samples into three distinct groups based on textural and mineralogical variations. Two samples (MG1 and MG3) are coarse-grained and range compositionally from alkali feldspar granite to granite, whereas sample MG2 is medium-grained and granitic in composition. Sample MG4 is fine-grained and inequigranular, exhibiting a micro-porphyritic texture with an alkali feldspar granite composition. The studied samples show noticeable variations in grain morphology, intergranular boundary relationships, intragranular fracturing, and

degree of mineral alteration. Modal mineralogical analysis indicates that, in addition to the essential minerals, i.e., quartz, alkali feldspar, and plagioclase, all samples contain variable but appreciable amounts of muscovite along with accessory minerals in trace quantities. The medium-grained sample (MG2) contains relatively higher proportions of plagioclase and muscovite compared to the coarse-grained and fine-grained varieties. Physico-mechanical properties, including unconfined compressive strength (UCS), unconfined tensile strength (UTS), shear strength, water absorption, and specific gravity, were determined and correlated with petrographic features. The highest UCS values were recorded for MG1, whereas the lowest values were observed for MG4, with MG2 and MG3 exhibiting intermediate strength characteristics. Based on UCS values, all samples fall within the moderately weak to moderately strong rock strength categories and display acceptable ranges of specific gravity and water absorption for potential construction applications. A comparative evaluation suggests that rock strength is influenced more significantly by petrographic attributes beyond grain size alone. These key controlling factors include the modal proportions of quartz and plagioclase, the quartz-to-total feldspar ratio, grain shape and intergranular boundary irregularity, the abundance of intragranular fractures, and the degree of mineral alteration. Collectively, these characteristics govern the engineering suitability of the Malakand Granite as a construction material in the region.

Keywords: Malakand Granite; Petrography; Physico-mechanical properties; Grain size; Textural control; Mineralogical control; Construction material; Northwestern Pakistan

Experimentally Constrained Nonlinear Site Response Analysis of Islamabad Soils Using Integrated Resonant Column and Cyclic Triaxial Data

Muhammad Yasir[1,2*], Waqas Ahmed[1], Hammad Raza[3], Muhammad Waseem[4]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [2]Pakhtunkhwa Energy Development Organization, Government of KP, Pakistan; [3]Department of Civil Engineering, University of Engineering and Technology Taxila, Taxila 47080, Pakistan; [4]Department of Civil Engineering, University of Engineering and Technology Peshawar, Peshawar 25120, Pakistan

[*]Email: myasir6755@uop.edu.pk

This study presents an integrated geotechnical and site-specific nonlinear ground response assessment of Islamabad, Pakistan, to evaluate the influence of local soil conditions on seismic ground-motion amplification. The methodology combined field investigation, laboratory index testing, resonant column and cyclic triaxial testing, shear-wave velocity characterization, and one-dimensional nonlinear site response analysis. Thirty boreholes were investigated across Islamabad, and recovered samples were tested for index and dynamic soil properties, including grain-size distribution, Atterberg limits, moisture content, and specific gravity. The subsurface soils are predominantly low-plasticity silts

and silty clays, mainly classified as ML and CL-ML, indicating fine-grained alluvial deposits with low to moderate plasticity. Resonant column tests defined the small-strain stiffness and damping response, whereas cyclic triaxial tests extended the characterization to medium and large strain levels. The two datasets were integrated to develop continuous laboratory-calibrated modulus reduction and damping curves for nonlinear modeling. Ten representative soil profiles were developed using borehole logs, unit weights, index properties, and locally calibrated SPT-based shear-wave velocity estimates. Based on Vs_{30}, profiles S1 to S8 were classified as BCP 2021 Site Class C, whereas S9 and S10 were classified as Site Class D. The profiles were analyzed in DEEPSOIL v7.0 using the GQ/H nonlinear constitutive model, with laboratory-calibrated curves used as the principal input for experimental nonlinear response analysis. The nonlinear analyses indicate dominant short-period amplification within approximately 0.1–0.4 s. Spectral amplification factors generally range from about 1.5 to 2.3, with the strongest amplification occurring in intermediate-depth Site Class C profiles where impedance contrast and strain-compatible stiffness promote resonance. Nonlinear deformation is concentrated mainly in the upper 5 to 10 m of the profiles, whereas deeper Site Class D profiles distribute strain over greater thickness but do not show a sustained long-period spectral plateau. The laboratory-calibrated results further indicate that stiffness degradation becomes pronounced beyond about 0.1% shear strain, while damping increases to approximately 10 to 15% at larger strains, thereby limiting excessive amplification through hysteretic energy dissipation. Overall, the findings demonstrate that experimentally constrained nonlinear site response analysis is essential for realistic seismic demand assessment in Islamabad and that Vs30-based classification alone may not adequately capture the effects of local stratigraphy, impedance contrast, and measured nonlinear soil behavior.

Keywords: Nonlinear site response; Ground-motion amplification; Dynamic soil properties; DEEPSOIL analysis; Islamabad

Tectono-Petrographic Controls on the Mechanical Behavior of Matiltan Granodiorite, Kohistan Island Arc

Izaz Aziz[1]*, Waqar Ahmad[2], Shah Fahad Alam[2,3], Israr ud Din[2], Shahid Ullah[1], Ihtisham Ullah[2]

[1]Mineral Testing Laboratory, Mineral Development Department, KP; [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan ; [3] Geological Survey of Pakistan, Quetta/Islamabad, Pakistan

[*]Email: azykhan172@gmail.com

The Matiltan area of upper Swat, northern Pakistan, located within the Kohistan Island Arc, exposes highly deformed granodioritic rocks that provide a great chance to study the interaction of tectonics, petrographic, and geotechnical behavior. This study uses field structural analysis, petrographic inspection, and laboratory-based geotechnical testing to assess the mechanical and mineralogical properties of the Matiltan Granodiorite. Field observations reveal prominent foliation tendencies and various fracture sets, indicating complicated

deformation caused by regional tectonics. The rose diagram analysis reveals primary stress directions of NW-SE, ENE-WSW, and NE-SW. Petrographic analysis shows a medium- to coarse-grained granodiorite composed primarily of plagioclase (~40%), quartz (~28%), orthoclase (~14%), and mafic minerals (~18%). The granular texture is hypidiomorphic, with deformation features such as undulatory extinction and grain boundary modification. Geotechnical testing shows unconfined compressive strength (UCS) values of 65-190 MPa (average ~132 MPa) and uniaxial tensile strength (UTS) of 6-11 MPa. The low tensile-to-compressive strength ratio (~0.06) indicates brittle rock behavior. These properties are heavily controlled by mineralogy, microstructure, and deformation history. The combination of structural, petrographic, and geotechnical data implies that Matiltan Granodiorite is appropriate for low- to moderate-stress engineering applications, but must be carefully considered in high-stress settings such as tunneling. This study sheds light on rock behavior in tectonically active arc environments, as well as contributing to engineering geology and crustal evolution research.

Keywords: Kohistan Island Arc; Granodiorite; Petrography; Geotechnical properties; Structural geology; Rock mechanics

Integrated Geomechanical and Petrographic Assessment of the Lockhart Limestone: A Comparative Study of Potwar and Hazara Basins, Pakistan

Mubariz Hassan[1,2], Faisal Shah[1, 3*], Tariq Mahmood[4]

[1]Department Earth Sciences, Abbottabad University of Science and Technology, Havelian, Pakistan; [2]Department of Earth Sciences, University of Lille 1, Cité Scientifique, 59655 Villeneuve d'Ascq, France; [3]Department of Earth Sciences, COMSATS University Islamabad, Abbottabad, Pakistan; [4]OGDCL, Islamabad, Pakistan

[*]Email: faisalshah322@gmail.com

The Potwar and Hazara Basins host wide-spread exposures of the Lockhart Limestone, a Paleocence carbonate sequence with significant potential as a construction aggregate. This study attempts to provide an integrated geomechanical and petrographic assessment of the Lockhart Limestone exposed near Dhak Pass (Potwar Basin) and Margala Pass (Hazara Basin) in order to evaluate its engineering suitability and to examine the influence of petrographic attributes on its mechanical behavior. Representative limestone samples were analyzed for standard geotechnical and aggregate quality tests including specific gravity, water absorption, sulphate soundness, Los Angeles abrasion, and uniaxial compressive strength (UCS), complemented with petrographic thin-section analysis. The investigated limestone exhibits a mean specific gravity of 2.71 and low water absorption values (0.52–0.53%), indicating low effective porosity and a dense carbonate framework. Los Angeles abrasion values of 14.5% at Dhak Pass and 15.6% at Margala Pass, together with sulphate soundness values are 0.61% and 0.59%, respectively, reflect high resistance to mechanical degradation and weathering processes. UCS values range from 29.75 MPa at Dhak Pass section to

23.27 MPa at Margala Pass section, indicating relatively enhanced mechanical competency in the Potwar Basin succession. Petrographic investigation classifies the limestone as predominantly wackestone, packstone, and grainstone composed mainly of calcite and benthic foraminiferal bioclasts, with subordinate clay minerals, dolomite, and iron oxides. The carbonate fabric records multiple diagenetic modifications which include micritization, cementation, and recrystallization, alongside variably developed microfractures partially filled with calcite and ferruginous material. These microstructural heterogeneities are more pronounced in the Margala Pass section and exert a significant control on aggregate strength and durability. The absence of reactive silica phases and less abundance of deleterious material indicate a negligible susceptibility to Alkali–Silica Reaction (ASR) and Alkali–Carbonate Reaction (ACR) with Ordinary Portland Cement (OPC). Correlation of geomechanical and petrographic data indicates that enhanced mechanical performance is associated with high UCS values having calcite rich, well cemented microfacies, whereas lower UCS values correspond to increased microfracturing, bioclast content, and localized argillaceous input. The results suggest that fabric integrity, degree of cementation, bioclasts abundance, and diagenetic alterations constitute the principal controls

Theme 4: Applied Geophysics & Subsurface Imaging

Root Water Uptake (RWU) Investigation Using Time-Lapse Electrical Resistivity Tomography (TL-ERT): Implications for Improved Agricultural Management in Dry Lands of Oman

Rahma Al Breiki, Muhammad Younis Khan*

Department of Earth Sciences, Sultan Qaboos University, Oman
**Email: m.khan1@squ.edu.om*

Water scarcity poses a significant challenge to agricultural productivity in arid and semi-arid regions, where efficient use of soil moisture is essential for sustaining crop growth and food security. Root water uptake (RWU) is a key process that governs the movement of water from the soil to plants. Yet its spatial and temporal dynamics remain difficult to characterize with conventional point-based methods. This study explores the use of time-lapse Electrical Resistivity Tomography (TL-ERT) to monitor RWU and root-zone soil moisture dynamics in dryland agricultural settings. Because soil electrical resistivity is strongly influenced by water content, repeated ERT surveys, calibrated with direct soil moisture measurements, can image seasonal wetting and drying patterns associated with irrigation, rainfall, and plant water use. Time-lapse resistivity models reveal active root uptake zones and quantify soil water depletion over time, providing high-resolution information on crop water use and root activity. The results demonstrate the effectiveness of ERT as a non-invasive, time-efficient approach for continuous monitoring of subsurface moisture dynamics (root-zone processes) and support precision irrigation strategies. The agro-geophysical approach contributes to improved agricultural

water management, enhanced crop productivity, and the sustainable use of limited water resources in dryland ecosystems.

Keywords: Time-lapse electrical resistivity tomography; Root water uptake; Soil moisture dynamics; Precision irrigation

Application of Unsupervised K-Means Clustering in Classification of Electrofacies and Analysis of Petrophysics for Hydrocarbon Reservoir Evaluation in the South Kohat Basin, Pakistan

Abdullah Ashraf, Sarfraz Khan*

National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan

**Email: sarfraz_nceg@uop.edu.pk*

This study investigates the petroleum reservoir potential of the Palaeocene Lockhart, Hangu, and Patala formations in the Kohat Basin, Pakistan, by integrating petrophysical analysis and unsupervised K-means electrofacies clustering (Zhang and Postaire, 1994) on well log data from Makori-01, Manzalai-02, and Sumari Deep X-01. Key reservoir parameters, including porosity (12–18%), shale volume (Vsh < 20%), and water saturation (Sw < 40%), were derived using density-neutron crossplots, gamma-ray log interpretations, and Archie's equation (Archie, 1942). The Lockhart Formation exhibited the most favorable reservoir quality, with 15% of its intervals classified as high-porosity (14–18%), low-Sw (<35%) electrofacies (EF2, EF4), correlating to fractured limestone. The Hangu Formation showed heterogeneous sandstone reservoirs, where 23% of intervals (EF13, EF15) demonstrated moderate porosity (12–16%) and Sw < 40%, aligning with fluvial-deltaic depositional models (Ahmed et al., 2014; Jan et al., 2019). The Patala Formation, though predominantly shaly (EF1, EF3), revealed localized sandstone electrofacies (EF6) with porosity ~12%. Cross-validation confirmed strong alignment ($R^2 = 0.78$) between electrofacies clusters and petrophysical "sweet spots," with 85% consistency to stratigraphic markers (Ghani et al., 2022). These results resolve vertical heterogeneity and identify untapped reservoir zones, challenging prior dismissals of the Patala Formation (Ali et al., 2022). The workflow advances reservoir characterization in structurally complex basins, offering a 30% improvement in lithological discrimination over conventional methods, as demonstrated in Himalayan foreland analogs. This study underscores the Kohat Basin's potential for unconventional hydrocarbon exploitation, particularly in the Lockhart and Hangu formations, and advocates for machine learning-driven approaches in frontier exploration.

Keywords: Electrofacies; K-Mean Clustring; Reservoir Evaluation; Petrophysics; Kohat Basin

Analysis of HVSR Data by applying Modified Centroid-Based K-means Algorithm: A case study from Karim Abad, Hunza, Northern Pakistan

Sarfraz Khan*, Ghazanfar Ali Khattak, Muhammad Hanzala

National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan

**Email: sarfraz_nceg@uop.edu.pk*

The Nakamura Horizontal-to-Vertical Spectral Ratio (HVSR) technique for site characterization has seen increased use in many studies to obtain seismo-stratigraphic information on similar subsoil. However, similar HVSR peaks of stratigraphic origin still have a subjective element in identifying the true peak. In this study, a modified non-hierarchical centroid-based algorithm is applied to the acquired HVSR data to produce micro-hazard zone maps of the northern Hunza region of Pakistan. The results reveal that the fundamental frequency fo and soil amplification range from 1.1 to 3.5 Hz and 1.03 to 5.14 mm, respectively. These site-specific parameters indicate moderate to high vulnerability of the soil to a catastrophic earthquake event of maximum 5.5 M from the surroundings (especially the HinduKush region). Centroid-based K-means clustering also yields two groups through the interpretation of HVSR data (fundamental frequency and soil amplification). Cluster validity tests were applied to assess the quality of the cluster solution. These results present the similarities and dissimilarities among different soils in relation to similar or dissimilar vulnerability characteristics. The final maps have been generated in ArcGIS by integrating the results of cluster analysis and the interpretation of HVSR data. The maps indicate that the southeastern and southwestern sites have a high risk of earthquake damage to structures due to high amplification.

Keywords: HVSR; Site characterization; K-means clustering; Seismic microzonation; Hunza region

Exploration of Mineralized Prospective Zones through Integrated Geophysical Investigations at Ziarat-Balanosh Area, District Chagai, Balochistan, Pakistan

Shahbaz Muhammad*, Muhammad Kamran

Geological Survey of Pakistan, Quetta/Islamabad, Pakistan

**Email: geoshahbazmj@gmail.com*

Pakistan is amongst the most active geodynamic regions of the world, as it lies at the intersection of major tectonic plates. Especially, its southwest part (volcano-magmatic Chagai belt of Baluchistan) hosts a prolific variety of economic mineral reserves. To explore its hidden treasures, the Geophysics Division of the Geological Survey of Pakistan (GSP) carried out the integrated geophysical investigations comprised of ground magnetic survey and induced polarization (IP) measurements at Ziarat Balanosh area, a shrine and village located at 20 km west of Chagai city within the district. Chagai. The objective of these investigations was to explore the metallic minerals prospect in the study

area. The study area of 55 km2 was initially covered by magnetic observations with 100 meters of profile and station spacing. The total magnetic anomaly map showed a variation of magnetic intensity from -730 to +590 nT. Moreover, low and high magnetic zones were delineated in 2D/3D magnetic maps, which were interpreted as the likely presence of hydrothermal alteration zones of the host rocks and revealed possible intrusive mineralized bodies/veins compelled to be further explored through IP investigations. The study area actually represents the aeromagnetic anomaly (AMA) No. 47, delineated by the aeromagnetic survey conducted in 1976-77 by Photosur Inc. of Montreal, Canada, for GSP. The behavior of this AMA suggests that it is indicative of base-metal targets and the environment of porphyry style of mineralization. It depicts that the results of present ground magnetics are in accordance with the aeromagnetic results. The surroundings of the study area have always been considered as a rich magnetic zone for magnetite occurrence; however, the low magnetic results were never taken into consideration. Targeting the low magnetic zones, a total of 13 IP profiles deploying Wenner configuration with 50 to 300 meters spacing were executed while taking electrical resistivity (ER) and IP measurements simultaneously. At profiles P-7 to P-13 within low magnetic zones (central to southern part of the study area), the zone of high chargeability (≈ 15-26 mV/V) with comparatively low resistivity (≈ <350-400 Ω-m) was delineated at subsurface; a good combination for the occurrence of sulphide mineralization associated with copper-gold prospect. The delineated area of the anomalous zone is about 800 x 500 meters at the subsurface and holds a magnetic amplitude of -1400 nT. Such a good results combination demonstrates an extensive, cohesive, and voluminous sulphide system at the subsurface and acts as a convincing drilling target for both precious and base metals. The integral analysis of the area geology, findings of present geophysical investigations, and their comparison with the successful geophysical studies at nearby AMA No.18 & 19, suggest a promising prospect for mineral exploration in the area in terms of sulphide mineralization, such as iron-copper and associated minerals within the proposed zones recommended for further investigation efforts and exploratory drilling as well.

Keywords: Chagai volcanic arc; Ground magnetic survey; Induced polarization; Hydrothermal alteration zones; Porphyry copper mineralization; Sulphide mineral exploration

Geophysical Modelling of Batura Glacier Internal Structure and Ice Thickness Through Ground Penetrating Radar (GPR)

Irfan Ullah*, Saifullah Khan, Shah Faisal

Bacha Khan University, Charsadda, Charsadda, Pakistan
**Email: dr.irfanullah.geo@bkuc.edu.pk*

The current accelerating trend of the climatic change has impacted the already stressed, extensively the fresh water resources of the country. Pakistan fresh water sustainable supply is mainly safeguarded by the glacier melt which constitutes almost half of the annual river water flow. The glaciers are therefore

playing a vital role in the country's food security sustainability and hydro power generation sustenance. The evaluation of the glaciers is of great importance to refine our predicting model to the more accurate forecast, which could be augmented only by inputting more data about the glacier modelling such as, its thickness, internal structure, total water content, rate of water supply and its prospect characterization for a future GLOF event. In this study we have evaluated the ablation zone of the Batura glacier with a GPR antenna of 20 MHz. The field setup for data acquisition is performed with the Model 3200 MLF Multiple (Adjustable) Low-Frequency 16-80 MHz antenna, a specialized GPR sensor utilized for deep penetration. The main advantage of this 16-80 MHz antenna is due to its variable transmitter/receiver geometry capability. The result of Batura glacier has shown that the Batura glacier has a thick coating (3-8 m, on average) of granitic debris both above, suspended inside and below the ice levels. The GPR electromagnetic signal cannot penetrate deeper below these debris layers. The stones scatter the input signal and make it difficult for the transmitter antenna to pick up any signals. An Ice layer of probable thickness 8 to 15 meter on average is visible below the debris coat layer. The ice surface is covered in a thick layer of debris, but below that, there is nothing but no reflection perhaps mainly due to the pool of debris below at most of the locations, in some other places, however, there are some visible ice layers stacked in some parts. Other than this, the data is largely unable to offer any more in-depth information.

Keywords: Climate change; Glacier hydrology; Batura glacier; Ground penetrating radar; Debris-covered glacier; GLOF hazard assessment

Ice Sheet/Cover Thickness Estimation and Characterization of Passu Glacier Through Ground Penetrating Radar (GPR)

Irfan Ullah*, Mehmood Alam, Shah Faisal

Bacha Khan University, Charsadda, Charsadda, Pakistan
**Email: dr.irfanullah.geo@bkuc.edu.pk*

The Hindukash, Karakoram, and Himalayas (HKH) of Pakistan and the surrounding region are referred to as the third poles due to the presence of numerous glaciers beyond the polar regions. The geomorphological, geological, and geophysical characteristics of the country contribute to an exceptional river system that ensures a continuous supply of melt water from the glaciers. The contribution of water flow from these glaciers to the river system in Pakistan constitutes nearly fifty percent of the total annual flow. The melting of glaciers is likely influencing water availability, thereby enhancing the country food security and supporting its predominantly agriculture-based economy. The glaciers in the northern region are consistently at risk of glacial lake outburst floods (GLOF) due to formation of new and expansion of existing the supra-glacial, en-glacial and sub-glacial lakes and an increased rate of melting due to current climatic change trends. The frequencies of GLOFs event are increasing every year throughout the region. Supra-glacial lakes can be identified and monitored through RS/GIS techniques but en-glacial and sub-glacial lakes need

advance instrumentation like GPR for the detection and monitoring for accurate subsurface analysis. In this study we have evaluated the ablation zone of Passu glacier with GPR antenna of 20 MHz. The Passu glacier its much cleaner and pure ice (owing to low debris suspended load). Technically all of these measurements took place in the ablation zone, where the ice thickens and exhibits layers as a result of temporal and systematic separation. The main feature of the result is, the strata like distribution of the ice layers. The overall schematic interpretation is an upper 20-25-meter colder ice layers, following by a water rich temperate extensive lens between 25 to 75 meter and lower deformational zone related to flow flooding, this model is consistent with typical temperate valley glacier in compressional flow zones.

Keywords: Hindu Kush–Karakoram–Himalaya; GLOF; Ground penetrating radar; Glacier monitoring; Passu Glacier

Theme 5: Geoinformatics, Remote Sensing, Natural Hazards & Disaster Risk Reduction

A DPSIR-Based Geospatial and SWAT Modelling Approach for Sediment Source Identification of the Tarbela Reservoir, Upper Indus Basin

Nimra Arshad[1], Nausheen Mazhar[1*], Paul Passy[2], Muhammad Ali[3]

[1]Department of Geography, Lahore College for Women University, Pakistan; [2]Department of Geography (UMR PRODIG), University of Paris, France; [3]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan

[*]Email: nausheen.mazhar@lcwu.edu.pk

Increased erosion in the Upper Indus Basin reduces reservoir capacity and jeopardizes the long-term viability of vital facilities like the Tarbela Dam, making sedimentation a significant threat to Pakistan's water and energy security. This study applies the -SWAT model to evaluate the temporal and spatial dynamics of sediment yield in the Upper Indus Basin. The Besham Qila Gauging Station, located upstream of Tarbela Dam, provided streamflow data for the model's calibration and validation. The model was developed using topography, soil, land use/land cover, and meteorological datasets. The model's reliability for watershed-scale evaluation was confirmed by calibration (1994–2008) and validation (2009–2023), demonstrating satisfactory performance statistics. Sub-basins 1, 4, 5, 6, 16, 17, 19, 21, 23, 24, and 25 were identified as major contributors to sediment yield, while Sub-basin 3 was identified as the primary sediment hotspot. Sediment transport was heavily concentrated during the monsoon season (with July as the peak contributing month) and yearly sediment output exhibited significant interannual variability. The Drivers, Pressure, State, Impacts and Response (DPSIR) framework was applied to systematically assess sediment-contributing factors within specific hotspot, subbasin 3, and to develop region-specific management and mitigation

strategies. Sub-basin 3 was identified as a critical sediment hotspot characterized by steep slopes, sparse vegetation cover, shallow unstable soils, and glacier melt influence, resulting in rapid runoff and severe erosion. The integrated geospatial and SWAT modeling approach revealed that natural geomorphic processes dominate sediment mobility in the region, significantly increasing downstream sediment loads and threatening the sustainability of the Tarbela Reservoir system. This study provides evidence-based recommendations for priorty sub-basins for sediment monitoring, erosion control, and watershed restoration. The results promote climate-resilient water infrastructure, sustainable hydropower management, and advancement toward SDGs 2, 6, 7, and 13. Pakistan's long-term water-energy resilience can be strengthened and reservoir storage protected bypriortizing sediment hotspot sub-basins for restoration, slipe stabilization, and continuous monitoring.

Keywords: Sediment yield modeling; Upper Indus Basin; SWAT model; Tarbela Dam; Watershed erosion; DPSIR framework

Seismic Hazard Assessment of Naulong Water Resources Development Project

Syed Kazim Mehdi

Mott MacDonald Pakistan Pvt. Ltd., Lahore, Pakistan
Email: sspkazim@gmail.com

The Naulong Water Resources Development Project (WRDP) is located at Latitude 28.44 N and Longitude 67.34 E in district of Jall Magsi, Baluchistan, Pakistan. Seismic hazard assessment (SHA) is prepared for calculating design and drawing design response spectrums at the coordinates of dam body with using active faults nearby project site, occurred earthquakes and local site conditions. The dam is located at the boundary of two major tectonic plates. This boundary, located west of the intersection of the Eurasian and Indian plates, has created the Kirthar Fold and Thrust Belt. The Kirthar Fault and Thrust Belt is one of the well-defined unequivocally active faults not only in Pakistan but also in World. The block where the dam is located is the hanging wall block of The Kirthar Fault and Thrust Belt. The hanging wall lies above the fault plane and moves relative to the footwall. In reverse and thrust faults formed by compression, the hanging wall is pushed up over the footwall, commonly at convergent boundaries like the Eurasian–Indian plate boundary. Obtaining Vs_{30} value is the first step for soil site conditions in updated revision of seismic hazard assessment. It is determined by the results from the studies of "Multi - Channel Analysis of Surface Waves (MASW), at site. With MASW studies, S-wave velocity measurements were applied to a depth of 50 m, also foreseeing stripping excavation. The average of S wave velocities from the bottom of the stripping excavation to a depth of 30 meters will represent the value Vs30. Vs30, the time-averaged shear wave velocity (Vs) to a depth of 30 meters. This value also gives an idea that the rocks are quite weak and easy to excavate and stiffness of local site conditions. This value is an important indication because the behavior of earthquake waves is related to Vs30 values based on design

procedures. As a result of MASW studies, 600 m/s (rock site) and 400 m/s (soil site) are measured for deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA). This level is symbolized "C", "C" and "B" site class according to Building Code of Pakistan - 2021, ASCE 7 – 16 and Eurocode 8, respectively. For the SHA, first of all, a circle with a radius of 200 km is drawn with the dam at the centre. The relationship of the faults within the circle with the project site is observed. From the year 1960 through 2025, a total of 2363 earthquake records are obtained greater than magnitude 4.00 or equal from seventeen different catalogues. Duplicated seismic events are removed from obtained all earthquakes according to reliability ranking resulting in 926 seismic events. Foreshocks and aftershocks are removed according to Gardner and Knopoff (1974) procedure. Moreover, completeness magnitude (Mc=4.0) is determined and data (403 records are left) is ready for the analysis. Finally, recurrence parameters are calculated with Weichert (1980) method. Open Quake (version 3.16.2) and EZ – FRISK (version 8.06) is run with using "Abrahamson et al. (2014)", "Boore et al. (2014)", "Campbell & Bozorgnia (2014)" and "Chiou & Youngs (2014)" ground motion prediction equations (GMPEs) for suggested researchers by International Commission on Large Dams (Bulletin 148, 2016). The final results for PSHA are given as the geometric mean of the Open Quake (Version 3.16.2) and EZ-FRSIK (Version 8.06) outputs.

Keywords: Naulong WRDP; SHA; Kirthar Fold and Thrust Belt; MASW; Open Quake, EZ-FRISK

Seismic Microzonation Studies for Skardu Master Plan 2040

Syed Kazim Mehdi

Mott MacDonald Pakistan Pvt. Ltd., Lahore, Pakistan
Email: sspkazim@gmail.com

As a part of the Skardu City Master Plan 2040, this study deals with the seismic microzonation and further development of building and land-use planning strategies. Restrictions to ensure mainstreaming of seismic hazards in the spatial planning and management of the Skardu City. Proposed area of interest starting from Hotto/Gamba to Hussainabad Skardu is approximately 135000 kanal. Due to the presence of three major mountain ranges, the geology of Skardu Valley is much diverse consisting of Metamorphic and Igneous rocks. Mostly all soil types are found in the Valley. Typically, the Valley has Mesozoic and Paleozoic -Precambrian soil types. Historical and instrumental seismic catalogues were developed for the Skardu region (within 200 km radius). The area has experienced intensities up to XI and earthquakes up to Mw 7.6. To determine the Soil Profile Types in accordance with Table 4.1 of Building Code of Pakistan, the area was classified into various seismic units. The resultant Soil Profile Types are SB = 760 m/sec, SC = 450 m/sec and SD = 200 m/sec. As per Deterministic Hazard Analysis the Karakoram strike-slip fault is present about 35 km NE of the Skardu City. A large amount of seismic activity having Mw ≥ 4.0 in the City, have been located from this fault. Maximum magnitude assigned

to the fault is Mw 7.7, while the computed PGA (H) = 0.2 g and PGA (V) = 0.13 g [PGA = Peak Ground Acceleration]. Based on geological maps, borehole logs, satellite imagery, and literature review, Skardu City (2040) was divided into three seismic microzones: Skardu Khas, Hussainabad, and Shigri Kalan. Hazard results are presented as horizontal hazard curves and uniform hazard spectra for return periods of 475, 975, and 2475 years. PSHA was performed using EZ-FRISK (Fugro, USA), and the resulting ground motion values (g) align with BCP 2021.Large number of construction activity is under progress in the Skardu City. It should strictly adhere to existing and state of art Building Code of Pakistan 2021. Areas with Soil Profile Types SB and SC are good for construction purposes. While Soil Profile Types areas of SD may be avoided in constructions goings-on. Further geological and geotechnical investigations are needed to identify active near-source seismogenic structures and support safer design decisions. Although natural hazards cannot be prevented, effective mitigation strategies can significantly reduce associated risks and damage.

Keywords: Seismic microzonation; Master Plan 2040; Soil profile types; PGA; EZ-FRISK software

Advancing Mangrove Mapping in Coastal Baluchistan through Multi-Temporal Remote Sensing and Machine Learning: Implications for Erosion and Sea Level Rise

Fiza Ashraf[1], Sawaid Abbas[1,2*]

[1]Smart Sensing for Climate and Development, Centre for Geographic Information System, University of the Punjab, Lahore, Pakistan; [2]Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong

[*]Email: sawaid.gis@pu.edu.pk; sawaid.abbas@connect.polyu.hk

Mangroves are vital coastal ecosystems that stabilize shorelines, store carbon, and support biodiversity, yet their accurate mapping remains challenging in intertidal regions where seasonal algal growth and tidal fluctuations alter spectral responses. This study investigates mangrove–algae spectral interactions in a biologically important lagoon with complex tidal dynamics using six Landsat 8 OLI images from 2022, covering a tidal range of 0.94–2.85 m across different seasons. Ground truth data from field surveys, high-resolution imagery, expert interpretation, and tidal records were used to distinguish mangrove and algal signatures, while training samples incorporated both spectral and temporal characteristics. A Random Forest classifier was applied with spectral indices and tidal-stage stratification to improve classification accuracy.Results show that tidal variation strongly affects class separability: at low tide, exposed algal mats closely resemble sparse mangroves, increasing misclassification, while at high tide, inundation of sparse mangroves further reduces separability. Dense mangroves remained stable (~27 km²), whereas algal extent fluctuated significantly from ~135 km² at low tide to ~28 km² at high tide. Sparse mangroves exhibited a strong negative correlation with tidal height ($r = –0.98$), indicating high sensitivity to inundation. The model achieved over 85% overall accuracy, with the best performance at intermediate tidal conditions. These

findings highlight the importance of tide-aware sampling, field validation, and multi-temporal analysis for reliable mangrove mapping in dynamic coastal environments such as the Indus Delta and similar intertidal ecosystems worldwide.

Keywords: Mangrove mapping; Tidal dynamics; Spectral confusion; Randomforest classification

Deterministic Seismic Hazard Assessment of High-Rise Buildings in Blue Area and New Blue Area, Islamabad

Chaudhary Fazeel Ahmad[1,2*], Fiaz Tahir[2], Osama Sajjad[2], M. Abdullah Cheema[2]

[1]National Engineering Services, Pakistan;
[2]University of Engineering and Technology Taxila, Taxila, Pakistan
[*]Email: fazeel.ahmad@nespak.com.pk

Islamabad, the capital city of Pakistan, is situated in a seismically active region governed by complex Himalayan tectonics, including the Main Boundary Thrust (MBT), the Rawalpindi-Islamabad Fault, and the Hazara-Kashmir Syntaxis. The rapid urban development of Blue Area and New Blue Area, the primary commercial and administrative cores of Islamabad has led to a construction of large cluster of high rise structures whose seismic performance under worst-case ground shaking scenarios has not been systematically evaluated. This study presents a Deterministic Seismic Hazard Assessment (DSHA) specifically tailored for high-rise buildings in these two zones, with the objective of establishing site-specific design ground motions that exceed the generalized provisions of the Building Code of Pakistan (BCP 2021). The methodology follows a multi-phase framework. First, a regional seismotectonic study is conducted, compiling a declustered earthquake catalogue from the ISC, USGS, and Pakistan Meteorological Department (PMD) databases within a 300 km radius of the study area. Active fault sources are characterized using Wells and Coppersmith (1994) scaling relations to estimate Maximum Credible Earthquakes (MCE) for each source, with the MBT scenario (Mw 7.5–7.8) identified as the controlling event. Secondly, site characterization is performed through geotechnical investigations, MASW surveys, and borehole data to determine Vs_{30} and ASCE 7-22 site classification for representative locations within the study area. Third, ground motion prediction is carried out using a logic-tree approach incorporating NGA-West2 GMPEs (BSSA14, CY14, ASK14, CB14) and the regional Sharma et al. (2009) model, implemented in OpenQuake Engine. Finally, one-dimensional nonlinear site response analyses are performed in DEEPSOIL v7 to propagate bedrock motions through the soil column and derive surface-level design response spectra. Preliminary results demonstrated that site-specific PGA and spectral accelerations at short periods significantly exceed BCP 2021 code values, highlighting an urgent need for site-specific ground motion studies in high-occupancy commercial zones. The resulting DSHA spectra will provide a rational basis for performance-based seismic design of high-rise buildings in Blue and New Blue Area, Islamabad.

Keywords: Deterministic seismic hazard; Islamabad; Main Boundary Thrust; GMPEs; Site response; Mid-high-rise buildings

Debris Flow Susceptibility and Propagation Analysis along the Karakoram Highway: Raikot to Khunjerab Pass, North Pakistan

Tanveer ul Haq[1,2*], Jian Huang[1], Said Mukhtar Ahmad[1], Muhammad Ali[2,3], Javed Iqbal Tanoli[2], Sundas Mehreen[2]

[1]State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610000, Sichuan, China; [2]Department of Earth Sciences, COMSATS University Islamabad, Abbottabad Campus 22010, Pakistan; [3]Department of Chemistry, Life Sciences & Environmental Sustainability, University of Parma, Parco Area delle Scienze 11/a, 43124 Parma, Italy

[*]Email: tanveerulhaq961@gmail.com

Natural hazards are the most frequent and destructive phenomena around the globe, specifically in the Himalayas-Karakoram mountainous terrain due to intense seismicity and climatic variability. Particularly, debris flow and rock falls are the most common geohazards which cause severe damage to life and infrastructure every year in these high mountain regions. This study aims to produce debris flow susceptibility and Flow-R propagation maps for the most critical section of the Karakoram Highway, from Raikot to Khunjerab Pass. Initially, a debris flow inventory of 111point locations was created through a comprehensive field survey. A total of ten conditioning factors were used including slope, slope aspect, curvature, Topographic Wetness Index (TWI), lithology, collapse material, fault buffer, stream buffer and elevation. These factors were analyzed using weighted overlay and Flow-R propagation to construct the final debris flow susceptibility maps. The debris flow inventory is divided into two parts as training (72 debris flows) and testing data (39 debris flows). The training data were used to rate parameters, and the testing data for validation; the resulting ROC curve yielded an AUC of 0.79, indicating the map is reliable for strategic and mitigation purposes. In the last step, Flow-R was employed to calculate the propagation extent and susceptibility. Using Google Earth, the collapsed materials of debris flow were marked and served as the input for Flow-R propagation. Thus, only area with high and very high susceptibility were considered as source zones capable of contributing to debris flow initiation along the investigated region, and the susceptibility map developed by Flow-R proved to be more effective for assessing debris flow hazards.

Keywords: Debris flow; Susceptibility mapping; Flow-R propagation; Karakoram Highway; Himalaya-Karakoram region

Debris Flow Probability Mapping Based on Their Triggering Mechanism in North Pakistan

Muhib Ullah Khan[1,2*], Chen Ninsheng[1,3], Khalid Latif[4], Ashfaq Ahmad[1,2]

[1]State Key Laboratory of Mountain Hazards and Engineering Resilience, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610299, China; [2]University of Chinese Academy of Sciences, Beijing 100049, China; [3]International Cooperation Center for Mountain Multi-Disasters Prevention and Engineering Safety, Yangtze University, Wuhan 430100, China; [4]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP

[*]Email: muhibkpk@yahoo.com

Debris flows in northern Pakistan are triggered by multiple distinct mechanisms. However, existing probability assessments have largely treated each trigger type in isolation, limiting the accuracy of hazard characterization and constraining the development of region-wide risk management strategies. To address this critical gap, we delineated the whole of northern Pakistan, including Gilgit-Baltistan Province and the Chitral and Kohistan districts of Khyber Pakhtunkhwa, and developed a class-specific indicator system that assigns tailored predictor sets to three debris-flow categories: Rainfall-Triggered Debris Flow, Glacier Debris Flow, and Glacial Lake Outburst Debris Flow. This framework captures the climatic, morphometric, tectonic, hydrological, and glaciological controls relevant to each triggering mechanism. Four machine learning models were trained within a standardized preprocessing pipeline incorporating median imputation, standardization, and Pearson collinearity filtering. CatBoost, TabPFN, LightGBM, XGBoost, and their ensemble model were applied. The ensemble model outperformed the individual models, achieving AUC values of 0.942, 0.915, and 0.920 for Rainfall-Triggered Debris Flow, Glacier Debris Flow, and Glacial Lake Outburst Debris Flow, respectively. SHAP analysis revealed that the most important features for Rainfall-Triggered Debris Flow were median elevation, loose material volume, peak ground acceleration, and circularity ratio. For Glacier Debris Flow, the dominant predictors were glacier slope, glacier mass loss rate, circularity ratio, glacier volume, peak ground acceleration, and tectonic uplift. For Glacial Lake Outburst Debris Flow, the most influential factors were glacier slope, circularity ratio, peak ground acceleration, and tectonic uplift. This study offers a reproducible, multi-model framework for comprehensive debris flow probability mapping under multi-triggering mechanisms, providing actionable outputs to support resilience planning and disaster risk reduction across the northern Pakistan region.

Keywords: Debris flow; Multi-trigger mechanisms; Susceptibility mapping; Machine learning; Northern Pakistan

Mapping Active Landslides along the Karakoram Highway Alternate Route in North Pakistan

Saad Khan[1, 2*], Said Mukhtar Ahmad[3]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [2]GIS and Space Applications in Geosciences (GSAG), National Centre of GIS and Space Applications (NCGSA), Institute of Space Technology, Islamabad, Pakistan; [3]State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China

[*]Email: saadkhan@uop.edu.pk

Slow-moving active landslides pose a significant threat to infrastructure, particularly along highways that cross tectonically active mountain belts. In high-altitude mountainous regions, identifying and assessing such landslides is difficult due to limited accessibility, extensive spatial coverage, a lack of versatile detection methods, and the inherently complex behavior of mass movements. In this research, we utilized Sentinel-1 Synthetic Aperture Radar data spanning from 2015 to 2024 to identify active landslides along two key segments: the alternate route of the Karakoram Highway (Chitral–Gilgit) and the main Karakoram Highway section (Gilgit–Khunjerab). By integrating phase gradient stacking with a deep learning network, we detected a total of 1,037 active landslides across the study area. Subsequently, time-series InSAR analysis was conducted on selected large-scale landslides to determine their displacement rates and deformation patterns, which revealed line-of-sight velocities as high as −81 mm per year. The reliability of these detections was confirmed through cross-validation with Google Earth imagery and previously published landslide inventories for the Karakoram Highway region. The findings illustrate the spatial distribution of active landslides within the uplifting mountainous terrain, identify zones of potential instability, and provide valuable insights for hazard mitigation and risk assessment, particularly, for less-monitored economic roadways located in orogenic settings.

Keywords: Active landslides; InSAR analysis; Sentinel-1 SAR; Karakoram Highway; Deep learning detection

Landslide hazard risk assessment and susceptibility mapping by integrated hydro-geomorphological approach for Soan river basin, in Potwar region of Pakistan

Muhammad Yaseen[1*], Muhammad Kaleem Sarwar[2], Sohail Abbas[3], Muhammad Imran[1], Syed Imran Naqvi[4], Syed Naeem Husnain[4]

[1]Centre for Integrated Mountain Research (CIMR), University of the Punjab, Qaid e Azam Campus, Lahore-Pakistan; [2]Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan'; [3]College of Geography and Environmental Science, Key Research Institute of Yellow River Civilization and Sustainable Development and Collaborative Innovation Center on Yellow River Civilization of Henan Province, Henan University, Kaifeng, 475004, China; [4]Department. of Environmental Sciences, National College of Business Administration & Economics (NCBAE)

[*]*Email*: yaseen.cimr@pu.edu.pk

Natural hazards, including landslides, avalanches, floods, and debris flows, can result in significant property destruction and loss of human life, particularly in mountainous regions. The Potwar region, located within the Himalayan foothills of Pakistan, is recognized as a mountainous area that is susceptible to landslides. This research aims to identify and delineate potential landslide hazard zones utilizing a multi-criteria approach within a Geographic Information System (GIS) and remote sensing framework, grounded in an analysis of various morphometric datasets. The hydro-geomorphological characteristics of the study area are effectively illustrated through the application of these morphometric metrics. Consequently, all morphometric data are synthesized to produce a landslide susceptibility map, which has proven advantageous for forecasting areas at risk for landslides. The study area encompasses a basin measuring 6,545 square kilometres. Findings indicate that the high landslide susceptibility zone predominantly resides in the upper section of the basin, with additional dispersed areas of very high susceptibility located in the upper middle and lower middle sectors. This high-risk zone comprises approximately 27% of the total basin area. Conversely, the intermediate landslide susceptibility zone represents 17% of the basin's overall expanse. Other morphometric indicators yield values that are considerably lower than those identified for the very high and high landslide susceptibility zones, thus categorizing this particular zone as moderate in terms of vulnerability. The low susceptibility zone accounts for 38% of the basin's area. The investigation conducted in this basin derived several key insights: (1) The very high landslide susceptibility zones correlate with regions that exhibit vulnerabilities stemming from both drainage conditions and topographical features. (2) Morphometric analyses suggest that a high drainage density coupled with steep rock surfaces are pivotal factors contributing to landslides in this locality, which are likely exacerbated by monsoonal rainfall. (3) The zones classified as extremely high in landslide susceptibility are associated with intense runoff, seasonally saturated bedrock conditions, and

elevated erosion rates, whereas zones with low susceptibility are characterized by stable slopes and moderate erosion intensity.

Keywords: Landslide susceptibility; Morphometric analysis; GIS and Remote Sensing; Potwar region; Drainage density; Himalayan foothills

GIS-Based Landslide Hazard Zonation in a Seismically Active Mountain Belt: Earthquake Conditioning Parameters, A Case Study of Batagram, Northern Pakistan

Aneeza Munir[1*], M. Qasim Mirza[1], Muhammad Farooq Ahmed[1], Fatima Ijaz[2]

[1]Geological Engineering Department, University of Engineering and Technology Lahore, Pakistan; [2]University of Engineering and Technology Lahore, Pakistan

[*]Email: aneezamunir004@gmail.com

Earthquake-induced landslides are a major hazard in northern Pakistan due to the frequent earthquakes, especially in the region of Hazara Kashmir Syntaxis, where the Batagram study area is situated. The study area is mainly influenced by the major active tectonic features, like the Main Boundary Thrust and Jhelum Fault etc. This research investigates the link between seismic activity as one of the main causes of landslides in northern Pakistan using a GIS-based hazard-based mapping and assessment. The earthquake data (epicenter and magnitude etc.) data was utilized to derive (through GIS tool) the seismic conditioning factors like earthquake density, distance to epicenters, magnitude, and magnitude influence. The GIS Based Analysis showed many seismic events occur within 15–50 km of landslides, indicating a strong spatial link between seismicity and slope instability. The earthquake data encompasses microseismicity (less than 3.0 Mw) and moderate to large earthquakes (>5.0 Mw), reflecting the active tectonic, while subsequent moderate to large events have contributed to progressive reactivation through cumulative weakening and failure. The methodological framework integrates seismic and geo-environmental parameters (slope, lithology, distance to river and NDVI) within ArcGIS. Conditioning layers were standardized and combined using a weighted overlay, with weights determined by literature and expert judgment. This integration resulted in a continuous landslide susceptibility index, which was classified into hazard zones using natural breaks. Results show high-probability zones are linked to elevated magnitude values, earthquake density, and proximity to seismic corridors. The study identifies three mechanisms for earthquake-induced landslides: (i) coseismic triggering by major seismic events, (ii) postseismic weakening from repeated low-magnitude earthquakes, and (iii) pronounced slope-driven effects under seismic loading conditions. Findings demonstrate seismic parameters improve landslide forecasting. This study provides a framework for further seismic based landslide hazard assessment and supports risk mitigation and land-use planning in tectonically active regions.

Keywords: Earthquake-induced landslides; Landslide susceptibility mapping; Seismic hazard; Hazara Kashmir Syntaxis; GIS analysis

Integrated Chemical Index of Alteration and Magnetic Susceptibility Constraints on Weathering-Controlled Landslide Triggering Mechanisms along Sheringal-Kumrat Road, Dir Upper, KP, Pakistan

Ihtisham Islam[1,2*], Muhammad Rizwan[1], Cheng Xin[1], Waqas Ahmed[3], Zhong Mengting[1], Ikramud Din[2]

[1]State Key Laboratory of Continental Evolution and Early Life, Department of Geology, Northwest University, Xi'an 710069, China; [2]Department of Geology, Shaheed Benazir Bhutto University Sheringal, Dir Upper 18050, Khyber Pakhtunkhwa, Pakistan; [3]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan

[*]Email: ihtisham.islam@sbbu.edu.pk

The role of mineralogical alteration and physicochemical weathering in preconditioning slopes for failure remains insufficiently quantified in crystalline metavolcanic terrains. This study integrates Chemical Index of Alteration (CIA) and mass-specific magnetic susceptibility (χ) data to evaluate weathering intensity and its influence on landslide triggering mechanisms. Major oxide geochemistry indicates moderate to advanced chemical alteration, with elevated CIA values reflecting progressive feldspar decomposition and transformation into clay-rich secondary minerals. Such alteration enhances porosity, reduces intergranular cohesion, and promotes hydrophilic clay accumulation along structural discontinuities. The magnetic susceptibility values across all four landslides range from 1.06×10^{-5} to 3.48×10^{-4} SI, indicating predominantly paramagnetic to weak ferromagnetic behavior with localized strong ferromagnetic enrichment. The presence of 10^{-4} SI values suggests partial preservation of primary magnetite, whereas 10^{-5} SI values reflect progressive oxidative alteration and enhanced chemical weathering. The heterogeneity in susceptibility within individual landslides suggests variable weathering intensity and uneven distribution of ferromagnetic minerals, likely influenced by slope position and geomorphic processes. The observed reduction in magnetic susceptibility in highly altered samples suggests oxidative breakdown of ferromagnetic phases during chemical weathering. This mineralogical transformation corresponds with increased microfracturing and loss of mechanical competence. The combined CIA–χ relationship reveals that chemically intensified zones coincide with magnetically depleted domains, marking sectors of advanced mineral destabilization. These weathered horizons act as mechanically weakened layers that concentrate pore-water pressure during intense rainfall events, thereby facilitating shear failure initiation. The results demonstrate that integrated geochemical–magnetic proxies provide a robust framework for identifying pre-failure weathering thresholds and delineating potential landslide-prone zones in complex lithological settings. This multidisciplinary approach enhances predictive capability for slope instability assessment in tectonically and climatically active mountainous regions.

Keywords: Chemical weathering; Magnetic susceptibility; Landslide triggering; Metavolcanic terrains; Slope instability

Geospatial Modeling of Landslide Susceptibility in Hazara Division, Khyber Pakhtunkhwa, Pakistan: An Integrated Approach Using GIS and Remote Sensing

Syed Tanvir Shah[1], Saud Anwar[1,2*], Abdullah Khan[1], Shaban[1,2], Bakhtiar Ahmad[1], Ihtisham Ullah[1,2]

[1]Department of Geology, Abdul Wali Khan University Mardan, KP, Pakistan;
[2]National Centre of Excellence in Geology, University of Peshawar, Peshawar
[*]Email: saudanwar522@gmail.com

The aim of this study is to produce a detailed landslide susceptibility map using the weighted overlay method of the Hazara Region, Pakistan. Multiple datasets, including slope, elevation, distance to streams, buffer valleys, roads, rainfall, curvature, drainage density, lithology, soil, aspect ratio, active fault maps, and land-use/land-cover (LULC) maps, are used to assess the susceptibility of areas that are prone to landslide hazards. The Digital Elevation Model (DEM) generates slope and aspect ratio maps, highlighting terrain characteristics key to landslide failures. Steep slopes and certain aspects are identified as major contributors to landslides, while drainage density pinpoints areas with high water content, increasing landslide hazard. Lithology and soil maps help identify zones with weakly consolidated sediments and permeable soils. The active fault map, compiled from literature, shows structural weaknesses that may trigger landslides. The LULC map evaluates human activities' impact on landslide susceptibility. Using the weighted overlay method in ArcGIS, the area is categorized into low, medium, and high-hazard zones. Abbottabad, Kohistan, and Mansehra show high susceptibility, Battagram moderate, and Haripur low. These findings offer valuable insights for land use planning, disaster risk reduction, and decision-making to mitigate the impacts of landslides in the Hazara and similar regions.

Keywords: Landslide susceptibility; Weighted overlay method; Hazara Region; GIS mapping; Disaster risk reduction

Identification of Subsurface Dam Sites in Arid and Semi-Arid Regions of Balochistan Using GIS-Aided ELECTRE Technique

Faizan Dar, Zaheer Muhammad Malik[*], M. Sayyam Asif, Atiq Ur Rehman Tariq

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan
[*]Email: zaheer.malik@cewre.edu.pk

Surface reservoirs experience major dry-season water losses and security risks that can potentially be mitigated through subsurface dam (SSD) storage. Generalized mapping techniques often fail to identify feasible SSD sites under local terrain and hydrogeological constraints. Although GIS–MCDM studies identify slope, drainage, rainfall, and land cover as major controls on recharge potential, many applications rely on compensatory overlays that obscure critical

aquifer storability limitations. A screening-and-ranking framework that first narrows feasible SSD zones at scale and then applies a non-compensatory outranking logic to prioritize candidate sites under conflicting constraints has been largely missing. This study develops an integrated GIS–AHP–ELECTRE approach in which five regional criteria (slope, stream network, rainfall, LULC, and soil texture) are standardized and combined using an AHP-weighted overlay approach. The suitability map shows that only 0.06% of Balochistan is highly suitable, concentrated along low-gradient alluvial corridors. Ten candidate sites extracted for preliminary assessment are evaluated against twelve site-specific criteria using ELECTRE concordance–discordance analysis (C* = 60.6, D* = 0.38) to derive an outranking-based priority order. The results show that SSD feasibility is structurally sparse and governed by non-compensatory trade-offs. The framework converts province-scale spatial ambiguity into a ranked, decision-ready shortlist, identifying SSD-3 as the most robust candidate for field verification. The framework provides an auditable and transferable decision-support protocol for SSD planning in arid and semi-arid regions.

Keywords: Subsurface dams; GIS–AHP–ELECTRE; Site suitability analysis; Groundwater storage; Balochistan

Mapping Water Persistence and Change in the Great Salt Lake (Utah, USA): A Spatio-Temporal Remote Sensing Approach

Muhammad Shahab[1*], Emad Ullah Khan[2], Fahad Alshehri[1], Irfan Ullah[3]
[1]Abdullah Alrushaid

[1]Chair for Earth Science Remote Sensing Research, Geology and Geophysics Department, King Saud University, Riyadh 11451, Saudi Arabia; [2]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Kraków, Poland; [3] Rayyan Resources for Geological Survey and Exploration, Saudi Arabia
[*]Email: mshahab.c@ksu.edu.sa

Spatio-temporal dynamics of surface water are critical indicators of hydrological variability and environmental change in arid and semi-arid regions. This study presents a comprehensive assessment of long-term surface water dynamics in the Great Salt Lake region, Utah, USA, using the JRC Global Surface Water Dataset within the cloud-based Google Earth Engine (GEE) environment. The analysis is based on multi-decadal Landsat program imagery spanning the period from 1984 to 2021, enabling consistent and high-resolution (30 m) monitoring of surface water variability. A suite of hydrological indicators including water occurrence, absolute change, normalized change, seasonality, recurrence, and transition classes was extracted to quantify both spatial and temporal variations in water extent. The study area was delineated to encompass the Great Salt Lake basin, and all datasets were pre-processed, clipped, and analyzed within a uniform geographic coordinate framework. Particular emphasis was placed on the transition layer, which categorizes water dynamics into ten distinct classes representing stable, seasonal, and transitional hydrological states. Quantitative analysis revealed that stable permanent water constitutes approximately 35.28% of the total water-covered area, representing the core lake system. However, a

substantial proportion of the region is undergoing hydrological decline, with permanent water loss accounting for 21.61% and seasonal water loss contributing an additional 10.94%. These findings indicate a pronounced net reduction in surface water extent over the study period. In contrast, newly formed permanent and seasonal water bodies represent only minor fractions (0.20% and 4.84%, respectively), suggesting limited compensatory expansion. Transitional dynamics are also significant, with 9.23% of the area exhibiting conversion from permanent to seasonal water, reflecting degradation in water permanence. Furthermore, temporary and highly dynamic water classes together account for over 13% of the study area, highlighting the increasing variability and instability of hydrological conditions, particularly along lake margins and adjacent low-lying basins. Spatial analysis (JRC Global Surface Water Dataset within the cloud-based GEE) demonstrates that water loss is predominantly concentrated along the periphery of the lake, where shallow depths and climatic sensitivity amplify the effects of evaporation and reduced inflow. Seasonal and temporary water classes are widely distributed in transitional zones, indicating fluctuating hydrological regimes influenced by interannual climate variability and anthropogenic pressures. The results underscore the vulnerability of the Great Salt Lake to ongoing environmental change, including prolonged drought conditions and upstream water diversion. The results were validated using historical Google Earth and Sentinel-2 imagery using randomly generated points across permanent, seasonal, and transitional water classes using visual comparison method. This study highlights the effectiveness of integrating long-term satellite observations with cloud-based geospatial analysis for monitoring large-scale hydrological systems. The findings provide critical insights into the extent, magnitude, and patterns of surface water change in the Great Salt Lake region, offering valuable information for water resource management, environmental monitoring, and climate adaptation strategies.

Keywords: Surface water dynamics; Google Earth Engine; JRC Global Surface Water; Great Salt Lake; Hydrological variability

Satellite Evaluation of Temperature and Rainfall Variability's Influence on Drought Indices in South Punjab, Pakistan

Muhammad Laraib, Arsam Ahmad Awan, Muhammad Atiq Ur Rehman Tariq*, Abdullah Nadeem, Farazeen Khizer

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan

**Email: atiq.tariq@gmail.com*

This study evaluates the impact of rainfall and temperature variations on drought conditions across South Punjab, Pakistan, during the period 2010-2020 using satellite-based remote sensing techniques. Rainfall data from the Soil Moisture to Rainfall (SM2RAIN) and temperature data from the Climate Prediction Center (CPC) were used to derive three drought indices: Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), and Deciles index (DI), computed at a six-month temporal scale representing hydrological

seasons (October–March and April-September). The drought years 2016, 2018, and 2019 were identified based on the convergence of all three indices. To assess drought impacts on vegetation and surface conditions, these indices were compared with MODIS-derived 16-day composites of the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). The results revealed that SM2RAIN outperformed CHIRP in South Punjab with higher correlation (0.71–0.79) and lower RMSE (73.65–117.61 mm), particularly in Bahawalpur and Bahawalnagar. Drought indices (SPI, RDI, DI) revealed moderate winter droughts (2012, 2018) and severe summer droughts (2016, 2018, 2019), with partial recovery post-2017. Furthermore, NDVI and EVI peaked in March and September, aligning with crop cycles, and declined in June and December due to heat and post-harvest stress. EVI showed greater sensitivity in detecting vegetation changes across mixed land-use areas. The integration of meteorological indices with MODIS products demonstrates the effectiveness of remote sensing tools in monitoring drought patterns and supporting climate-resilient planning in semi-arid regions of Pakistan.

Keywords: Drought monitoring; Remote sensing; SPI and RDI; MODIS vegetation indices; South Punjab Pakistan

Updated Seismic Hazard Assessment of United Arab Emirates (UAE) Using Areal Source Models

Muhammad Waseem*, Muhammad Mesum Abbas

University of Engineering and Technology Peshawar, Pakistan
**Email: m.waseem@uetpeshawar.edu.pk*

Rapid urban and infrastructure development in the United Arab Emirates (UAE) necessitates updated seismic hazard characterization despite the region's generally low-to-moderate seismicity. This study presents a classical probabilistic seismic hazard assessment (PSHA) integrating seismotectonic modeling with open-source computation using the OpenQuake Engine. A homogenized earthquake catalogue ($M_w \geq 4.0$) covering earthquakes from 1905–2026 was compiled by merging records from the United States Geological Survey (pre-1925 events) and the International Seismological Centre (1925–2026). The initial catalogue of 4,688 events was declustered using the Gardner–Knopoff space–time window algorithm, producing 3,166 independent earthquakes. Completeness analysis was performed using the visual cumulative method. Seismic source modelling incorporated ten shallow crustal zones, one deep seismic source zone, and one Makran subduction source zone. The bounded Gutenberg–Richter recurrence relationships to estimate seismicity parameters for each areal source, while epistemic uncertainty was addressed through a logic-tree framework combining six GMPEs i.e. Abrahamson et al. (2014), Boor et al. (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014) for shallow crustal tectonics and Zhao (2006) and Kanno (2006) for subduction interface and subduction intraslab environments. The hazard calculations assumed reference rock conditions (Vs30 = 760 m/s) as site conditions vary spatially across the UAE along the territory which can be

incorporated using the Fa and Fv parameters from the building code. The results show strong north–south hazard variation across the UAE. For the 225-year return period, peak ground acceleration and spectral accelerations remain moderate, with Ss ≈ 0.08–0.31 g and S1 ≈ 0.02–0.09 g, dominated by shallow regional seismicity. At the 975-year return period, hazard increases toward northern emirates with Ss ≈ 0.22–0.46 g and S1 ≈ 0.07–0.11 g, representing design-level shaking. For the 2475-year return period (2% probability of exceedance), long-period effects from Makran subduction earthquakes become significant, yielding Ss ≈ 0.08–0.71 g and S1 ≈ 0.02–0.16 g, with maximum values observed in Ras Al Khaimah and Fujairah respectively. The results indicate the dominant influence of regional tectonics rather than local faulting (Dibba Fault System in Oman) and provide an updated, transparent hazard reference for seismic design and regional seismic hazard assessment in the Arabian Peninsula.

Keywords: Probabilistic seismic hazard assessment; OpenQuake Engine; UAE seismicity; Ground motion prediction equations; Makran Subduction Zone

Spatiotemporal Analysis of Groundwater Storage Using Physics-Informed Neural Networks and Analytical Tools in Bannu Division, Pakistan

Naveed Wahab[1], Zaheer Muhammad Malik[1], M. Atiq Ur Rehman Tariq[1], Muhammad Waqas[2], Amjad Masood[1*]

[1]Centre of Excellence in Water Resources Engineering, UET, Lahore, Pakistan;
[2]Department of Civil Engineering, UET, Peshawar, Pakistan
[*]Email: amjadmasood06@gmail.com

Groundwater depletion threatens water security, agriculture, and livelihoods in semi-arid regions such as Bannu Division, Pakistan, where reliable local-scale groundwater storage information remains limited. Existing GRACE/GRACE-FO studies estimate regional groundwater changes, but coarse resolution and sparse in-situ data mask sub-regional variability and reduce management usefulness. This study addressed this gap by downscaling GRACE-derived groundwater storage from 55 km to 5 km using a physics-informed machine-learning framework, followed by k-means clustering, STL decomposition, heat-map analysis, and frequency distribution. Results showed groundwater storage anomalies from +120 to −180 mm, with 61% of grid cells persistently negative and central depletion hotspots ≤−140 mm covering 28–32% of the division. Downscaling increased spatial variance by 2.3 times while preserving long-term trends. Four groundwater regimes were identified; two depleted clusters occupied 56% of the area and showed mean anomalies of −90 to −150 mm. Seasonal variability explained 55–70% of variance, while depleted clusters declined by 4–7 mm yr^{-1}, causing cumulative losses of 80–100 mm. Negative anomalies increased from 38% of months in 2003–2009 to 72–76% after 2015. The study concludes that depletion is structurally persistent, mainly driven by abstraction exceeding episodic recharge and recommends high-resolution

monitoring, localized abstraction control, efficient irrigation, stronger in-situ validation and predictive climate–abstraction modeling.

Keywords: Groundwater depletion; GRACE downscaling; Machine learning; Bannu Division; Hydroclimate variability

Development of a Satellite-Based Air Quality Dashboard for Spatiotemporal Monitoring of Smog and Pollutants in Punjab, Pakistan

Nimra Arshad, Nausheen Mazhar*

Department of Geography, Lahore College for Women University, Pakistan
**Email: nausheen.mazhar@lcwu.edu.pk*

This work proposes and demonstrates a satellite-based approach using Copernicus Sentinel-5P data to a monitor and assess air quality fluctuation and smog dynamics in Punjab, Pakistan. The region experiences severe winter smog from October to December due to vehicle emissions, industrial activity, agricultural burning, and meteorological factors such as temperature inversions, which poses serious health hazards and lead to persistently poor air quality. Punjab's current ground-based monitoring networks are few and inadequate, limiting spatial coverage and hindering real-time assessment of key pollutants (NO_2, SO_2, CO, O_3, HCHO, and CH_4). This project develops a novel framework that integrates cloud-masking, spatiotemporal analysis, interactive visualization, and Sentinel-5P satellite observations to enable high-resolution air quality monitoring across Punjab. The approach distinguishes between smog-free (January-September) and smog-affected (October-December) periods, detects pollution hotspots, and supports evidence-based decision-making in environmental management and policy development. Aligned with Sustainable growth Goals 3, 11, and 13, the proposed framework contributes to public health protection, sustainable urban growth, and climate change mitigation through data-driven air quality management. Ultimately, this approach improves air quality monitoring in Punjab by enabling timely interventions, reducing exposure to hazardeous pollutants, and promoting long-term environmental sustainability. By leveraging freely available satellite data, the system enhances regional environmental monitoring capability and makes it more accessible to policymakers, researchers and public. It also contributes to early warning systems for smog events, improves spatial understanding of pollutant dispersion, and encourages coordinated cross-sectoral action. By combining Earth observation technologies and analytical tools, this research provides a scalable model applicable to other regions facing similar air quality challenges worldwide.

Keywords: Air quality monitoring; Sentinel-5P; Smog; Google Earth Engine; Spatiotemporal analysis

Lethality-Driven Hazard Ranking for Underground Coal Mining Fatalities in Pakistan: A CRITIC–MARCOS Analysis of Technical Failure Pathways

Atif Javed[1], Rana Muhammad Asad Khan[2*], Ghufran Ur Rehman[2], Hira Hameed[3]

[1]Central South University of China, China; [2]Pak-Austria Fachhochschule (PAF-IAST), Haripur, Pakistan;[3]Department of Physics, University of Punjab

[*]Email: masadkhan87@gmail.com

Underground coal mining in Pakistan continues to face recurrent fatal accidents caused by methane explosions, toxic gas exposure, roof and ground failures, flooding, blasting, mechanical haulage, and electrical hazards. Although earlier studies have reported accident patterns in Pakistan's coal sector, limited work has converted recent fatal incident evidence into an objective and reproducible hazard prioritization framework. This study develops a data driven engineering assessment of fatal hazard pathways in Pakistan's underground coal mines using a newly compiled public source dataset covering the period 2016–2026, supplemented by a historical listing of incidents from 2011–2015 for contextual background. After excluding security related attacks that do not represent underground technical hazard mechanisms, 30 fatal technical incidents involving 164 fatalities from the 2016–2026 period were retained for the primary analysis. A decision matrix was constructed using three quantitative criteria: accident share, fatality share, and lethality factor. The Criteria Importance Through Intercriteria Correlation (CRITIC) method derived objective criterion weights from the variability and conflict structure of the data, while the Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) method ranked hazard pathways according to their relative criticality. CRITIC results assigned the highest weight to lethality factor, followed by accident share and fatality share, indicating the importance of considering both occurrence and fatality intensity. The MARCOS ranking identified methane/gas explosion as the highest priority fatal hazard pathway, followed by flooding/water inrush, suffocation/toxic gas exposure, and collapse/ground failure. Flooding showed high lethality but was represented by fewer documented events; therefore, its ranking should be interpreted cautiously. These findings highlight methane control, ventilation reliability, gas monitoring, emergency preparedness, and ground control management as urgent engineering priorities for reducing fatality risk in Pakistan's underground coal mines.

Keywords: Coal mine safety; Underground coal mining; Fatal accident analysis; Methane explosion; CRITIC–MARCOS method; Risk prioritization

Tectonic Controls on Large Bedrock Landslides in the Hunza Valley: An Interpretable Machine Learning and SHAP-Based Assessment

M. Farooq Ahmed[1*], Iqra Hassan[1], Adnan Siddique[2], E. Naseer[2], Othmar Frey[3]

[1]Department of Geological Engineering, University of Engineering and Technology Lahore, Pakistan; [2]Remote Sensing and Spatial Analytics Lab. Information Technology University (ITU), Lahore, Pakistan; [3]Chair of Earth Observation and Remote Sensing, ETH Zurich, Zurich, Switzerland

[*]Email: mfageo@uet.edu.pk

Understanding the relative roles of tectonic and climatic controls on large bedrock landslides remains a key challenge in active orogenic belts. In this study, remote sensing, field observations, and interpretable machine learning tools are integrated to investigate the factors governing large, deep-seated landslides in the Hunza region. A field-validated landslide inventory, derived from anomalous topographic and geomorphic signatures, was used as a training mask. An ALOS PALSAR DEM and multi-source geospatial data including; GNSS-derived crustal velocities, slope, aspect, curvature, elevation, drainage proximity, fault proximity, seismic hazard, rainfall, topographic wetness index, and vegetation cover. This study quantitatively assesses the relative contributions of multiple conditioning and triggering factors controlling large bedrock landslides using interpretable machine learning models. Three models (Random Forest, XGBoost, and MLP neural network) were trained and interpreted using SHapley Additive exPlanations (SHAP) to quantify feature contributions. All models achieved high predictive performance (AUC up to 0.98). SHAP-based interpretation reveals that tectonic parameters, particularly crustal velocity and proximity to active thrust faults, consistently rank as the best predictors of landslide occurrence, whereas rainfall likely acts as a secondary or transient trigger. Furthermore, spatial clustering of deep-seated landslides (e.g., Mayoon, Miacher, and Budalas) within zones of elevated deformation (~25 mm/yr) within the active collision zone is consistent with progressive rock mass weakening and long-term slope destabilization. These results highlight the importance of tectonic forcing in preconditioning large bedrock landslides, with climatic inputs facilitating episodic reactivation. The integration of geodetic data with interpretable machine learning provides a quantitative framework for improving landslide hazard assessment in such tectonically active mountainous regime.

Keywords: Tectonic controls; Bedrock landslides; Interpretable machine learning; SHAP analysis; Landslide susceptibility mapping; Hunza Valley

Theme 6: Energy, Petroleum Systems & Basin Analysis

Integrated Geological, Geochemical, and Geophysical Assessment of Hydrocarbon Source Rocks in the Kohat Basin, Pakistan

Shehzad Ali[1,2], Liaqat Ali[1], Khalid Latif[1*], Kashif Ishaq[1,2]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [2] Khyber Pakhtunkhwa Oil and Gas Company Limited, Peshawar
[*]Email: khalidlatif@uop.edu.pk

Hydrocarbon source rock assessment is fundamental to petroleum system development, particularly in structurally complex foreland basins. This study presents an integrated geological, geochemical, and geophysical evaluation of hydrocarbon source rocks in the Kohat Basin of Pakistan. Investigations were conducted on surface and ditch cutting samples from wells penetrating Jurassic to Paleocene stratigraphic successions, including the Datta, Samana Suk, Chichali, Hangu, Lockhart, and Patala formations. Total Organic Carbon (TOC) analysis and Rock-Eval pyrolysis were used to determine organic richness, kerogen type, and thermal maturity. Cross-plots of TOC, S1, S2, Hydrogen Index (HI), Oxygen Index (OI), Tmax, and Production Index (PI) were utilized to evaluate hydrocarbon potential and maturity trends across the studied intervals. Results indicate fair to good organic richness, with most TOC values below 2 wt.%. Kerogen types range from Type II/III to Type III, suggesting mixed oil- and gas-prone characteristics with a tendency toward gas generation. Thermal maturity spans from mature to peak oil and wet gas window stages, reflecting variable burial depths and tectonic evolution within the basin. Seismic interpretation reveals that the fold-and-thrust structural framework exerts significant control on source rock distribution, hydrocarbon migration, and trap formation. Overall, the studied formations can be considered potential hydrocarbon source rocks within the basin. This integrated approach enhances understanding of the petroleum system and provides valuable insights for future hydrocarbon exploration in the Kohat Basin.

Keywords: Source rock; Geochemistry; Seismic interpretation; Thermal maturity; Petroleum system; Kohat Basin

Reservoir Potential of the Upper Cretaceous Kawagarh Formation, Orakzai Region, Pakistan: Insights from Microfacies and Diagenetic Analysis

Waseem Shah, Khalid Latif[*], Syed Ali Turab, Taimur Khan

National Centre of Excellence in Geology, University of Peshawar, Peshawar KP
[*]Email: khalidlatif@uop.edu.pk

Reservoir characterization and sedimentological characteristics of the Upper Cretaceous Kawagarh Formation were investigated at the Khamal and Andhkhel sections, District Orakzai. During fieldwork, activities involved section measuring, lithological logging, and photographic documentation. Collected

samples were used to prepare thin sections, which were subsequently examined petrographically under microscopes, along with SEM (scanning electron microscopy) analysis and plug porosity/permeability measurements to evaluate diagenetic effects on reservoir potential. The outcrop consists of limestone, marl, and shale intercalations. In the 64-meter Khamal section, 52 samples were analyzed, identifying four microfacies: 1) planktonic foraminifera mudstone, 2) dolomitized mudstone, 3) planktonic foraminifera wackestone, and 4) planktonic foraminifera packstone. Likewise, petrographic analysis of 25 samples from the 84-meter Andhkhel section identified four microfacies: 1) dolomitized mudstone, 2) planktonic foraminifera wackestone, 3) siliciclastic to dolomitic wackestone, and 4) bioclastic to planktonic foraminifera packstone. Microfacies analysis indicates deposition in an outer ramp environment. Diagenetic features include micritization, dolomitization, dissolution, pyrite precipitation, cementation, stylolitization, and fractures, representing marine, meteoric, and burial diagenetic processes. Dissolution, fracturing, and dolomitization increase porosity, whereas cementation, pyrite precipitation, and compaction decrease it. SEM analysis observed vuggy and intergranular porosity types. Plug porosity varied from 0.870% to 2.980%, with permeability ranging from 0% to 0.025 md, suggesting poor reservoir capacity for the Kawagarh Formation.

Keywords: Kawagarh Formation; Cretaceous; Sedimentology; Microfacies analysis; Diagenesis; Reservoir characterization

Thermodynamic Controls on Caprock Wettability: Analyzing Temperature and Pressure Effects on Natural Hydrogen Storage Integrity

Syed Muhammad Abdullah Bukhari[1*], Arshad Shahzad Ahmad Shahid[1]

[1]Department of Petroleum and Gas Engineering, University of Engineering and Technology Lahore, Pakistan

[*]Email: abdullahbukhari270@gmail.com

As Pakistan maps its geological potential for Underground Hydrogen Storage (UHS) to support a sustainable energy transition, identifying viable cap rocks in basins such as the Potwar and Lower Indus remains a critical challenge. The sealing capacity of these formations depends heavily on the capillary entry pressure (Pe) which is fundamentally governed by the dynamic wettability (contact angle) and interfacial tension of the rock-fluid system under varying subsurface conditions. This study presents a data-trend analysis of existing petrophysical literature to map the thermodynamic boundaries of cap rock integrity for hydrogen storage. By extracting and synthesizing dynamic high-temperature, high-pressure (HTHP) laboratory data across diverse lithologies, this research analyzes the isolated effects of temperature and pressure on the contact angles of evaporites (e.g., anhydrite, halite) versus organic-rich shales. Trend analysis indicates that evaporites generally maintain a strongly water-wet state even at elevated pressure regimes, preserving a high capillary threshold ideal for hydrogen containment. Conversely, organic-rich shales demonstrate pronounced wettability alterations, where shifting thermodynamic conditions

can transition the system toward a gas-wet state, significantly increasing the risk of hydrogen migration. This thermodynamic analysis provides a foundational petrophysical screening framework. By establishing the temperature and pressure limits at which specific cap rocks experience critical wettability shifts, this study offers reservoir engineers and geoscientists a data-driven metric for prioritizing domestic UHS pilot sites, ensuring long-term containment security for Pakistan's emerging green energy infrastructure.

Keywords: Underground hydrogen storage; Cap rock integrity; Wettability; Capillary entry pressure; Petrophysical analysis

The Investigation of Diagenetic Features to Interpret the Reservoir Rocks in the Middle Jurassic Shinawari Formation, Upper Indus Basin, Pakistan

Muhammad Salman[1], Fahad Ali[1,2*] Shiqi Zhang[2], Beenish Ali[1]

[1]Department of Geology, Bacha Khan University Charsadda, Khyber Pakhtunkhwa, Pakistan; [2]School of Geoscience, China University of Petroleum East China, Qingdao 266580, China

[*]Email: fahadalizai@yahoo.com

The Indus Basin of Pakistan is categorized as petroliferous and is comprised of geological formations ranging from Precambrian to Recent geological time. The basin is further subdivided into two sub-basins: the Upper Indus Basin (Kohat and Potwar sub-basins) and the Lower Indus Basin (Central and Southern sub-basins). In the Upper Indus Basin, the Middle Jurassic Shinawari Formation occurs as a thick, mappable unit, while its analogue in the Lower Indus Basin also consists of clastic and carbonate strata. The methodology adopted to interpret the reservoir characteristics of the Middle Jurassic rocks involves the development of a diagenetic model through petrographic study and software-based image analysis. Petrographic analysis was carried out using polarizing and scanning electron microscopy, while image analysis was performed using the freely available ImageJ software. The petrographic study indicates the presence of micritization, fracturing, vein formation, dolomitization, pyritization, cementation, and compaction, along with their subtypes. These diagenetic features were used to interpret a genetic diagenetic model and its effects on reservoir potential. Furthermore, photomicrographs of these diagenetic features were imported into ImageJ software to estimate porosity and permeability. The combined petrographic and software-based analysis shows that the identified diagenetic features in the Shinawari Formation significantly influence reservoir properties, suggesting that the Middle Jurassic Shinawari Formation has good potential for indigenous hydrocarbons. The current research is correlated with the Arab-D Formation to place the findings in a broader regional context, mainly based on reservoir quality characteristics.

Keywords: Indus Basin; Shinawari Formation; Diagenesis; Reservoir characterization; Petrographic analysis

Hydrocarbon Source Rock Characterization of Paleocene Coal in the Central Kurram Ranges of Pakistan

M. Younas[1], Khalid Latif[1*], Nowrad Ali[2], Hikmat Salam[3], Adil Khan[1], W. Shah[1]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]Deptt. of Geology, University of Peshawar, Peshawar 25120, KP, Pakistan; [3]Khushal Khan Khattak University, Karak, KP

[*]Email: khalidlatif@uop.edu.pk

Kurram District, situated in the northwestern segment of the Kohat Fold and Thrust Belt, contains geological formations ranging from the Jurassic to the Paleocene era, known for their potential in hydrocarbon generation. This study investigates coal samples obtained from the Paleocene Hangu Formation, located in the Central Kurram area of Khyber Pakhtunkhwa, Pakistan, to evaluate their quality and source rock potential. Coal samples were analyzed using organic petrographic and geochemical techniques to assess maceral composition, organic matter content, and thermal maturity. The analysis indicates that vitrinite macerals make up the majority of the coal composition, particularly collodetrinite (~80%), with minor inertinite and liptinite, indicating Type III kerogen. TOC ranges from 12.16% to 74.56%, and generative capacity values from 5.77% to 58.97%, suggesting moderate to excellent hydrocarbon potential. Thermal maturity is supported by S2 values >0.2 and elevated Tmax readings, though vitrinite reflectance values (0.68–0.78%) place the samples within the oil window. The discrepancy between high Tmax and relatively low VR values suggests vitrinite suppression, linked to minor liptinite enrichment whose structural composition characterizes (Type II) kerogen and promotes bitumen/hydrocarbon diffusion into vitrinite, thereby lowering its reflectance. Interpretation of multiple geochemical indicators, such as cross-plots of Oxygen Index, Tmax, and Production Index, along with the ternary maceral diagram, indicates that the coals are mature and possess high gas potential, capable of generating both dry and wet gas (condensates). S1-TOC relationship confirms that hydrocarbons are indigenous, though partial loss has occurred due to thin seams and stringers facilitating primary migration. Low Hydrogen Index values further support this. The depositional setting is interpreted as terrestrial under fluctuating oxidizing to anoxic conditions, favoring autochthonous organic accumulation. In conclusion, the Hangu Formation coal represents a viable source rock with superior quality compared to many Pakistani coals, which are typically moisture-rich and low-grade. They are categorized as bituminous coal with medium to high volatility, as well as hard brown coal, containing negligible water, thereby reflecting both significant hydrocarbon potential and energy value.

Keywords: Paleocene coal; Hangu Formation;Hydrocarbon potential; Organic geochemistry; Thermal maturity; Petrography; Vitrinite

Estimation of Pore and Fracture Pressure Gradients in Chanda Oilfield, Kohat Basin, Pakistan

Bahram Khan, Sarfraz Khan*, Muhammad Hanif

National Centre of Excellence in Geology, University of Peshawar, Peshawar, KP, Pakistan
**Email: sarfraz_qau@yahoo.com*

Abnormal pressures zones are the major problem in the drilling and exploration of oil and gas. Due to these abnormal pressure zones, several drilling challenges are faced, and overhead cost may result. This study is focused on the identification of these abnormal pressured zones using high resolution geophysical logs drilled through the reservoir formations of Chanda Oilfield, Kohat basin, Pakistan. Petrophysical analysis is carried out to identify clean and shaly zones. The well-known Eaton empirical method is used for calculation of overburden, pore pressure and fracture gradient. Based on the results, three overpressure zones are identified i.e. Patala Formation (Chanda-1), Chichali Formation (Chanda-1, -2 and Chanda Deep-1) and the contact of Mianwali and Chiddru formations (in Chanda Deep-1). Estimated outputs were calibrated and validated with the available direct downhole measurements (formation pressure measurements, LOT/FIT). Shear failure gradient was calculated using Mohr-Coulomb rock failure criterion to understand the wellbore stability issues in the studied field. Largely, the pore pressure in the reservoir formations is hydrostatic in nature, except the lower Cretaceous to upper Jurassic shales, which were found to be associated with mild overpressure regimes. The finding of this study will be used to reduce the non-productive time during drilling and exploration that prevent the hazardous activities associated with oil and gas exploration and drilling i.e., blow out and lost circulation and designing the casing point according to formation conditions. Furthermore, this study marks the normal and abnormal pressures zones in the selected wells of the Kohat basin and the results will help the oil and gas industry in safe and economical drilling.

Keywords: Pore and fracture pressure; Petrophyiscal analysis; Chanda Oilfield; Mud weight; Vertical stress; Eaton's method

Selection of Artificial Lift Method for Optimum Production from an Oil Well

Muhammad Kashif Ali[1*], Safia Nosheen[2], Jahanzeb Khan[1], Syed Deedar Ali Shah[1]

[1]Department of Petroleum and Gas Engineering, University of Engineering and Technology Lahore, Pakistan; [2]Department of Banking and Finance, University of Management and Technology Lahore, Pakistan
**Email: m.kashifali@uet.edu.pk*

The optimization of oil recovery from aging reservoirs involves the strategic application of artificial lift systems under specific well conditions. In this study, an exhaustive assessment of three significant artificial lift methods, Electric Submersible Pumps (ESP), Jet Pumps, and Sucker Rod Pumps (SRP) was conducted using the PROSPER simulation software. Each method was studied

under different reservoir pressures, water cuts, and operating parameters to assess its performance in improving oil recovery. The findings show that ESPs provide the highest production rates and economic payback in high-pressure conditions, while SRPs are more feasible in low-pressure and shallow-well conditions. Although Jet Pumps are relatively less efficient, they offer operational flexibility, particularly in wells with complicated geometries or high solid content. This study also strongly underscores the need for the customization of artificial lift systems to particular reservoir conditions and production objectives.

Keywords: Artificial lift systems; Oil recovery optimization; PROSPER simulation; Electric submersible pump (ESP); Reservoir engineering

Source Rock Characterization of the Trans Indus Ranges and Adjacent Areas, Pakistan: Implications for Hydrocarbon Generation and Prospectivity

Kashif Ishaq[1, 2], Khalid Latif[1*], Shehzad Ali[1, 2]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, KP, Pakistan; [2]KP Oil and Gas Company Limited, Peshawar, Pakistan
[*]Email: khalidlatif@uop.edu.pk

This study presents an integrated source rock evaluation using geochemical, geophysical, and spectroscopic techniques to assess hydrocarbon generation potential and prospectivity in the Trans Indus Ranges, Pakistan. Surface samples and ditch cuttings from Jurassic to Paleocene formations (Datta, Samana Suk, Chichali, Hangu, Lockhart, and Patala) were analyzed using Total Organic Carbon (TOC), Rock-Eval pyrolysis, and Raman spectroscopy. Raman spectroscopy, a non-destructive technique, was used to characterize organic matter and assess thermal maturity through D and G band parameters. Cross-plots of Rock-Eval pyrolysis–derived geochemical parameters were used to evaluate organic richness, kerogen type, and hydrocarbon generation potential. Raman spectral results show a decreasing trend in G peak position across samples, with a slight deviation in sample CP1 indicating variation in thermal maturity. Comparison with standard Raman fields after Wopenka & Pasteris (1993) indicates that all samples fall within the main kerogen field, suggesting early-stage thermal maturation. The petroleum system comprises multiple source rocks with effective sealing horizons. Geochemical and lithological evidence indicate several potential source intervals with varying maturity levels. Active oil seepages, including from Early Cretaceous source rocks, confirm a working petroleum system and support favorable conditions for hydrocarbon generation, migration, and accumulation. The stratigraphic framework further suggests the presence of a regional hydrocarbon kitchen with Jurassic to Paleocene source rocks in close proximity. However, long migration pathways and possible structural breaching are likely key factors limiting successful hydrocarbon accumulations in the area. Overall, the results highlight spatial variability in source rock quality and provide important insights into regional hydrocarbon prospectivity.

Keywords: Trans Indus Ranges; Source rock evaluation; Rock-Eval pyrolysis; Total Organic Carbon (TOC); Raman spectroscopy; Hydrocarbon prospectivity

Theme 7: Environmental & Soil Sciences, Climate Change & Hydrology

Design of Sustainable Water Distribution Systems for Urban Areas in Developing Countries

Shanza Arshad[1*], Mubashra Mahmood[2], Tanveer Ahmed[2]

[1]Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan; [2]Institute of Environmental Engineering and Research, UET, Lahore, Lahore 54890, Pakistan

[*]Email: engineershanzaarshad@gmail.com

This study provides guidelines for the design of a sustainable water supply scheme considering the management of water resources i.e., rainwater harvesting and water conservation. It was based on conducting a feasibility study to evaluate the possible benefits of proposed interventions and performing a cost analysis to check the cost- benefit analysis. Firstly, the water supply system without rainwater harvesting system was designed. Subsequently, rainwater harvesting potential was assessed for residential plots of 3-marla, 5-marla, and 10-marla sizes. The storage tank volume analysis was then performed. The storage tank volume was calculated using four different methods that included Sam Sam Water Rainwater Harvesting Tool Model, General Formula, Ripple Method and Equalization Method. The Sam Sam Water Rainwater Harvesting Model was found to be the most optimum method for the calculation of volume in our scenario. The calculated storage volume was divided into the rain barrel volume and the underground tank volume. Moreover, three cases are developed based on the different water demand % that is considered to be met through harvested rainwater. The Case I included the water demand of gardening, house cleaning and laundry which computes18%of the demand whereas the Case II included the demand for gardening, house cleaning, laundry and toilet flushing which constitutes the 44% demand and finally the Case III included the gardening and house cleaning that builds the 8% of the demand. Case I was selected because the rainwater is not enough to fulfill demand of Case II whereas the demand of Case III is too low, and the majority of rainwater is wasted. Now after the case selection and the storage volume computation the rainwater harvesting system was designed on the SWMM by using the LID of Rain Barrel. The system without and with Rainwater Harvesting System was run and the comparison of both systems is done. The effect on flooding and run-off for 2-year, 5-year and 10-year return period is observed. The implementation of RWHS led to an 8.6% reduction in average water demand and a 17.38% decrease in electricity consumption. The analysis further revealed substantial mitigation of urban peak flooding from individual houses, with reductions of 99.50%, 97.07%, and 91.91% for return periods of 2,

5, and 10 years, respectively, as evaluated using SWMM. At the community (society) level, flooding was reduced by approximately 20–24%. The estimated implementation costs of RWHS for 3, 5, and 10 Marla houses are Rs. 550,253, Rs. 670,890, and Rs. 1,112,283, respectively.

Keywords: Rainwater harvesting; Sustainable water supply; SWMM modeling; Urban flooding mitigation; Water resource management

Biodegradation of Polyvinyl Chloride, Polystyrene, and Low-Density Polyethylene by Environmental and Baker's Yeast Consortia in Freshwater Systems

Asma Azad, Abdullah Nadeem, Zaheer Muhammad Malik*

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan

**Email: zaheer.malik@cewre.edu.pk*

Microplastic pollution in freshwater ecosystems requires innovative bioremediation strategies. This study quantitatively evaluated the comparative biodegradation potential of an environmental yeast consortium isolated from a plastic-polluted freshwater reservoir and the industrial strain Saccharomyces cerevisiae against polyvinyl chloride (PVC), polystyrene (PS), and low-density polyethylene (LDPE) microplastics under simulated water treatment conditions. During 90-day incubation in synthetic freshwater medium, S. cerevisiae demonstrated significantly faster growth kinetics, achieving peak colonization (1.60-1.69 $\times 10^3$ CFU g^{-1} polymer) by Day 2, while the environmental consortium reached maximum density (1.16-1.67 $\times 10^3$ CFU g^{-1}) by Day 3. X-ray diffraction analysis confirmed statistically significant reductions in polymer crystallinity index (15-32%) across all treatments compared to abiotic controls, with the environmental consortium showing preferential efficacy against PVC and PS (28% and 25% crystallinity reduction, respectively), while S. cerevisiae was most effective against low-density polyethylene LDPE (30% reduction). Despite different colonization rates, both consortia induced measurable peak broadening and intensity reduction ($p < 0.05$) in XRD diffractograms, indicating substantial structural degradation. These findings provide quantitative evidence supporting yeast-based biological treatment as a viable supplementary technology for microplastic removal, with the environmental consortium offering specialized degradation capabilities suitable for nature-based systems, and S. cerevisiae presenting advantages for rapid, engineered water treatment applications.

Keywords: Microplastic biodegradation; Freshwater ecosystems; Yeast consortium; Saccharomyces cerevisiae; Water treatment applications

Integrating Groundwater Quality Indices with Machine Learning for Spatio-Temporal Irrigation Water Assessment in the Bahawalpur Irrigation Zone

Ahmed Aslam[1*], Zaheer Muhammad Malik[1], Muhammad Waseem[1], Muhammad Sayyam Asif[1], Muhammad Asad Abbas[1], Muhammad Atiq Ur Rehman Tariq[2]

[1]Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan; [2]College of Engineering and Science, Victoria University, Melbourne, VIC 8001, Australia
[*]Email: ahmedaslam1930@gmail.com

Groundwater quality plays a critical role in sustaining agricultural productivity, particularly in semi-arid regions where irrigation heavily depends on groundwater resources. This study presents an integrated framework combining groundwater quality indices (IWQI, EWQI, and GWQI), Geographic Information System (GIS) analysis, and machine learning (ML) models to evaluate the spatio-temporal dynamics of irrigation water quality in the Bahawalpur Irrigation Zone. A dataset comprising 12,026 groundwater samples collected over seven years during pre- and post-monsoon seasons was analyzed using key hydrochemical parameters including EC, SAR, and RSC. Spatial interpolation and seasonal trend analysis revealed a persistent core–rim gradient, where canal-fed central areas exhibited relatively better groundwater quality, while desert-facing peripheral zones showed continuous deterioration due to salinity accumulation and limited recharge. Among the tested ML models, Support Vector Machine (SVM) demonstrated the highest predictive performance, outperforming ANN, Random Forest, and AdaBoost with superior accuracy and generalization ability. The integrated GIS–ML framework effectively identified groundwater quality hotspots and seasonal variability patterns, providing a reliable decision-support tool for sustainable irrigation management and early risk assessment in groundwater-stressed agricultural regions.

Keywords: Groundwater quality; Irrigation water quality index; Machine learning; Spatio-temporal analysis; GIS mapping; Salinity hazards

Adsorptive Removal of Methylene Blue from Aqueous Phase Using Dalbergia sissoo Leaf Powder: Kinetics, Isotherms, and Mechanistic Insights

Mah e Sayyam[1], Anis Safir[2*], Saleem Nawaz[1], Shah Rukh[3], Bai-Bureh O'Bai Kamara[4,5], Muhammad Haroon Khan[1]

[1]Department of Chemistry, Islamia College University, Peshawar, Pakistan; [2]Department of Environmental Sciences, University of Peshawar, Peshawar 25120, Pakistan; [3]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [4]Magbosi Land Water and Environment Research Center (MLWERC), Mile 91, Sierra Leone, West Africa; [5]Agriculture Department, Central University, Sierra Leone
[*]Email: anissafir2019@gmail.com

Dye pollution is one of the major water pollutions that is causing decrease in photosynthetic activities beside their adverse health effects. In the current study synthesis of modified Dalbergia Sissoo (DS) leaf powder was carried out to use as an adsorbent to remove Methylene Blue (MB) from aqueous phase. Surface characterizations of adsorbents were conducted using the SEM, EDX, and FTIR methods. The effect of dosage, pH, dye concentration, temperature, shaking

time, and ionic strength on the adsorption was investigated systematically. isotherm models of Freundlich and Langmuir were applied on the adsorption data. MB dye adsorption data on DS best modeled by Freundlich isotherm model (R2 >0.99). The adsorption data at different time intervals were also plotted using kinetic models. Pseudo-second-order (R2 >0.99) was more successful in describing the adsorption kinetics of MB on DS. Adsorption is spontaneous, exothermic, and disordered as found by thermodynamic analysis. DS is discovered to be an improved adsorbent substance in the decontamination of dyes in wastewater.

Keywords: Dye pollution; Photosynthetic activities; Adverse health effects; Adsorption; Langmuir and Freundlich models

Demarcation of Bio-Climatic Altitudinal Zones of the Kaghan Valley, North Western Himalayas, Pakistan

M. Kaleem Sarwar[1], M. Yaseen[2*], Syed Imran Naqvi[3], Syed Naeem Husnain[3]

[1]Centre of Excellence in Water Resource Engineering, University of Engineering and Technology Lahore, Lahore, Pakistan; [2]Centre for Integrated Mountain Research (CIMR), University of the Punjab, Quaid-e-Azam Campus, Lahore, Pakistan; [3]Department of Environmental Sciences, National College of Business Administration and Economics, Pakistan

[*]Email: yaseen.cimr@pu.edu.pk

Demarcation of bio-climatic altitudinal zones are vital for the sustainable management of forest resources in a mountainous region. Three model areas for sustainable forest and mountainous region management have been defined for Kaghan Valley located in the NW Himalayas in Pakistan. Model Area-1 includes Balakot and Muzzafarabad, which have elevations ranging from 656m to 1650m above mean sea level (amsl). Envelopes for Area-2 models Manur and adjacent territories that range from 1651m to 2250m elevation, while Model Area-3 includes Saif-ul-Muluk and nearby zones ranging in elevation from 2251m to 5200m. The valley is serving as a watershed for two most significant dams, i.e., Tarbela and Mangla. In this region, we have been observing degradation and depletion of the forest during the last three decades. Historically, extensive forests had occupied practically the whole Tehsil Balakot of District Mansehra having an altitude below 3,300m. Currently, only about 26% of the forest cover remains on the steep to very steep top mountainous slopes; elsewhere, approximately 74% of the forests have been destroyed for grazing and Barani (rain-fed) farming. Guzara or Shamlat (common land) forests account for 20% of total forest cover and have been degraded to the point where they can no longer be categorized as forests; they are moderately wooded shrub land or shrub grassland. Merely 6% of the current forests are classified as reserved (state-owned) forests with extensive top cover and no grazing. Such a high rate of forest degradation implies that previous forest management strategies were inadequate and proved to be unsustainable in terms of ecosystem management.

Keywords: Bio-climatic zones; Forest management; Kaghan Valley; NW Himalayas; Forest degradation

Precipitation Trends and Change Point Detection over Time Using Pettitt Test, Mann-Kendall, and Innovative Trend Analysis in the Jhelum River Basin, Pakistan

Abdullah Nadeem, Arsam Ahmad Awan, Farazeen Khizer, Muhammad Atiq Ur Rehman Tariq*

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan

**Email: atiq.tariq@gmail.com*

Rainfall and other form of precipitation are important factors that are affecting ecological variations and agriculture in region. Therefore, it is necessary to accurately predict precipitation trends because it might be crucial for sustainable economic planning and development of a country. Therefore meteorologists, hydrologists and researchers are focusing on analyzing time series trends of precipitation. This research aims to analyze trends in seasonal and annual precipitation as well as geographical and temporal homogeneity of upper and lower Jhelum basins. Innovative trend analysis (ITA), Mann-Kendall (MK), and Sen's slope are used for trend analysis whereas change points in rainfall pattern are identified using Pettit's test. Of the 17 available precipitation stations, 12 stations were considered to have sufficient and reliable data for analysis; these stations were distributed across five sub-basins and were examined at both annual and seasonal scales. Twelve out of seventeen stations, were considered to have sufficient and useful precipitation data, distributed in Five sub-basins, were investigated at an annual, as well as at seasonal scale. It was concluded that high-altitude stations showed decreasing trend whereas low-altitude stations showed an increasing trend in annual precipitation. It was found that MK trend analysis is limited in results in comparison with ITA. At the annual scale, precipitation decreased at 8 of the 12 analyzed stations, 66.7%, and increased at 4 stations, 33.3%; decreasing trends included the high-elevation Astore and Naran stations, while increasing trends were observed at Balakot, Kotli, Palandri, and Mangla. Compared with the MK test, which classified trends only as increasing, decreasing, or no trend, ITA provided five trend categories and therefore captured more detailed precipitation variability. To improve precision and promptness of rainfall data gathering in Jhelum River basin, use of sophisticated autonomous climatic data recording devices is advised.

Keywords: Precipitation; Mann-Kendall; Pettitt's test; Sen's slope; Innovative Trend Analysis; Changepoint detection; Spatial and temporal variability

Groundwater Recharge: Modelling for Sustainable Groundwater Resources Management in Lahore Using Visual MODFLOW

Bisma Akmal, M. Usman Ashraf, M. Masood*, Ghulam Nabi, Muhammad Akbar

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan

**Email: masood@cewre.edu.pk*

The escalating global water crisis, driven by population growth, industrialization, and urbanization, is threatening its sustainability. Pakistan, with over 200 million people, is facing a severe water shortage. In Lahore, groundwater is a critical resource for domestic, agricultural and industrial needs. However, rapid urbanization has led to excessive groundwater extraction, depleting the aquifer. Since natural groundwater replenishment occurs slowly, artificial recharge techniques have become necessary for sustainable water management. This study evaluates the effectiveness of groundwater recharge methods, focusing on Lahore. Using a hydrological model, rainfall runoff data of study area was analyzed. Observation well data were imported to Visual MODFLOW to evaluate the impact of recharging techniques in groundwater was evaluated. Recharging was carried out using infiltration galleries, with recharging wells added for comparison. The results showed that the groundwater depletion rate in the area averaged 0.9 m/year, but infiltration galleries increased groundwater levels by 2 meters annually, compared to 1 meter from recharging wells. The groundwater level in the study area was initially at 218 m, but infiltration galleries raised it to 220 m, showing a superior performance over recharging wells. The study concluded that infiltrating 0.087 m/day of water through these galleries could significantly help maintain groundwater levels, demonstrating the importance of adopting effective groundwater recharge techniques for long term water sustainability.

Keywords: Groundwater recharge; Infiltration galleries; Visual MODFLOW; Aquifer depletion; Lahore

Spatiotemporal Assessment of Meteorological Drought in Saudi Arabia: Trends, Patterns, and Regional Variability

Amjad Masood[1], Amro Elfeki[2*], Anis Chabaani[2], Jarbou Bahrawi[2], Muhammad Atiq Ur Rahman Tariq[1]

[1]Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore, Pakistan; [2]Deptt. of Water Resources, Faculty of Environmental Sciences, King Abdulaziz University, Jeddah, Saudi Arabia

**Email: aelfeki@kau.edu.sa*

Drought is a natural hazard that arises from prolonged water scarcity, severely affecting crop growth, agricultural productivity, socioeconomic activities, and ecosystem sustainability. The primary driver of drought is extended periods of below-average precipitation. Saudi Arabia, located in an arid and water-stressed region, faces significant inter-annual rainfall variability, making it highly vulnerable to recurring droughts. Among the various indices developed for

drought monitoring, the Standard Precipitation Index (SPI) is the most widely used due to its simplicity and effectiveness. Analysis revealed negative trends across all drought years, beginning in the late 20th century and persisting until 2012. The dataset indicated very few extreme wet events, whereas multiple severe and extreme drought episodes were recoded, with SPI values ranging from a maximum of 3.87 to a minimum of -5.38. Furthermore, percentile mapping at the 90^{th} (10^{th}) and 95^{th} (5^{th}) thresholds of SPI provide valuable insights for policymakers, enabling them to design adaptive strategies and to apply focused interventions aimed at reducing the negative effects of droughts under certain conditions.

Keywords: Drought monitoring; Standardized Precipitation Index (SPI); Arid climate; Saudi Arabia; Precipitation variability

Assessing the Impact of Rainfall Variability and Anthropogenic Pressures on Groundwater Depletion in Lahore: A Spatio-Temporal Analysis from 2003 to 2023

Kandeel Sadaqat[1], Abdullah Nadeem[2*], Kashif Nazir[1]

[1]Institute of Space Science, University of the Punjab, Pakistan; [2]Centre of Excellence in Water Resources Engineering, UET, Lahore, Lahore 54890, Pakistan

[*]Email: abdullahnadeem910@gmail.com

Groundwater depletion is an escalating concern in rapidly urbanizing regions, driven by over-extraction and erratic precipitation patterns. Lahore, Pakistan, has experienced significant declines in groundwater levels over the past two decades, threatening long-term water security. This study quantifies the relationship between precipitation and groundwater levels from 2003 to 2023 using a combination of statistical and geospatial approaches. Pearson's correlation analysis revealed variable associations, with moderate positive correlations ($r \approx 0.38$) during wetter years and strong negative correlations ($r = -0.65$) in dry years, notably in 2018, highlighting the growing dominance of anthropogenic stress over natural recharge. Mann Kendall trend analysis confirmed a statistically significant decline in groundwater levels ($Z < 0$, $p < 0.05$), while spatial interpolation using Kriging and Inverse Distance Weighting (IDW) identified central and southern Lahore as critical zones of severe depletion. These findings underscore the urgent need for sustainable groundwater management, including artificial recharge, rainwater harvesting, and controlled extraction. Given limitations such as data gaps and interpolation uncertainties, future research should integrate remote sensing, high-resolution monitoring, and machine learning to enhance predictive modeling. Without immediate and coordinated intervention, Lahore's aquifers are likely to face continued depletion, emphasizing the need for a science-driven, integrated water resource management strategy.

Keywords: Groundwater depletion; Precipitation variability; Spatial interpolation; Urban water management; Mann-Kendall; Lahore

Evaluation of Graphene Oxide and Raw Graphene for the Adsorptive Removal of Arsenite from Contaminated Water and Soil

Asma Azad, Abdullah Nadeem, Zaheer Muhammad Malik*

Centre of Excellence in Water Resources Engineering, UET, Lahore, Pakistan
**Email: zaheer.malik@cewre.edu.pk*

Humanity is concerned about the existence of contaminants in water because drinking water with low levels of contaminants can have detrimental effects on one's health. Various technologies have been employed to lessen or completely eradicate these contaminants. Adsorption has been emphasized due to its inexpensive and straightforward removal process, and nanomaterials, such as graphene oxide, have been described as excellent adsorbents in environmental remediation due to their functional groups that provide stability, antifouling, and hydrophilicity—all of which are critical for the removal of arsenic from soil and water. Rapid industrialization raises the amounts of arsenic in soil, groundwater, and water bodies; this toxicity has caused disasters in emerging nations. The goal of this research is to synthesize graphene oxide (GO), a sophisticated nanomaterial adsorbent for the removal of dangerous arsenic from water. GO has demonstrated a high and quick capacity to remove arsenic. Because to surface complexation, electrostatic attraction, and ion exchange processes, it has a great affinity for both forms of arsenic through hydrophobic surfaces with large acidic groups and hydrophobic surfaces with hydrophilicity and contact. Furthermore, the adsorption process is undoubtedly impacted by the GO's thickness and porosity, the types of arsenic in the water, and the experimental setup. The titration technique was used for adsorption measurement, and the experimental results were compared to raw graphene, which has a restricted capacity for adsorption. GO achieved the highest adsorption in samples of arsenic-contaminated water and soil solutions. The findings show that GO can provide a promising adsorption capability for the removal of ionic arsenic from soil and water in the field of water purification.

Keywords: Graphene oxide; Arsenic adsorption; Water purification; Nanomaterial remediation; Contaminated groundwater; Adsorption kinetics

Exploring Alternate Options and Identification of Trade-Offs to Reduce the Environmental Burden in Nutrient Film Technique Hydroponic System Using Life Cycle Assessment

Abdullah Nadeem, Muhammad Atiq Ur Rehman Tariq*

Centre of Excellence in Water Resources Engineering, UET, Lahore, Pakistan
**Email: atiq.tariq@gmail.com*

Global food security is increasingly challenged by population growth, urbanization, land degradation, and water scarcity, highlighting the need for sustainable agriculture. Hydroponics, particularly the Nutrient Film Technique (NFT), provides resource-efficient food production but faces sustainability concerns due to energy-intensive operations and material choices. While hydroponics has been broadly assessed, few studies have examined trade-offs

between materials and energy sources in NFT systems using life cycle assessment (LCA). This study conducted an LCA of nine NFT scenarios combining three materials (PVC, PLA, and almond shell) with three electricity sources (grid mix, wind, and photovoltaic). Primary data were obtained from an operational hydroponic farm in Multan, Pakistan, with secondary datasets supplementing material inputs. The analysis was performed in GaBi using CML 2001 methods. Results indicated electricity source as the dominant factor influencing climate impacts, with wind power providing the largest reductions in global warming potential. Material choice significantly affected toxicity and resource burdens. Almond shell consistently outperformed PVC and PLA, especially with wind power, lowering greenhouse gas emissions, fossil resource use, and human toxicity, though increasing eutrophication. The study concludes that coupling renewable energy with waste-derived materials is crucial for advancing circular, low-impact hydroponic farming.

Keywords: Life cycle assessment (LCA); Hydroponic farming; Nutrient film Technique (NFT); Renewable energy integration; Sustainable agriculture; Circular economy

Modelling Climatic Parameters in Khyber Pakhtunkhwa Province Using Mann-Kendall and ARIMA Models

Muhammad Dawood

Department of Geography, Bahauddin Zakariya University, Multan, Pakistan
**Email: dawood.geography@bzu.edu.pk*

Climate change possesses dynamic characteristics essentially controlled by temperature and rainfall which can be studied using time series analysis. This study is an attempt to explore the temperature and rainfall flux and its trend prediction using Monte Carlo and ARIMA approaches in Khyber Pakhtunkhwa province, Pakistan. In this study, temperature and rainfall parameters were used as climatic parameters. For all the fifteen meteorological stations, data concerning temperature and rainfall were collected from Pakistan Meteorological Department (PMD). To achieve the study objectives, the temperature data as MM_{Max}, MM_{Min}, and M_{Avg} and rainfall data as mean monthly, mean annual and total annual were simulated and analyzed by applying Monte Carlo and ARIMA models. After modelling, the resultant analysis indicate that a notable temperature trend was detected in the meteorological stations of Chitral ($\alpha = 0.003$), Dir ($\alpha = 0.001$), Drosh ($\alpha = 0.04$), Peshawar ($\alpha = 0.0001$) and Cherat ($\alpha = 0.01$), whereas rest of the stations indicate slight variability. Similarly, in terms of rainfall, prominent trend was predicted in Saidu Sharif ($\alpha = 0.04$), Peshawar ($\alpha = 0.004$), Chitral ($\alpha = 0.06$), Kakul ($\alpha = 0.005$) and Balakot ($\alpha = 0.003$) meteorological stations. Contrary to this, the remaining stations illustrate no visible trend and expressed little fluctuation. Similarly, by using ARIMA model, the entire met stations exhibit variability and anomaly.

Keywords: Climate change; Time series analysis; ARIMA modeling; Monte Carlo simulation; Khyber Pakhtunkhwa Pakistan

Groundwater Arsenic Contamination and Human Health Risk Assessment in a Rural Region of Northwestern Pakistan

Muhammad Ayaz Khan[1*], Zafran Wazir[1], Shah Rukh[2]

[1]Department of Environmental Sciences, The University of Haripur, Haripur 22620, KP, Pakistan; [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan

[*]Email: ayazkhan@uoh.edu.pk

This study was conducted to investigate arsenic (As) contamination of drinking water and its health impacts in South Waziristan (Wana) Khyber Pakhtunkhwa, Pakistan. For this purpose, a total of 42 composite drinking water samples were collected from 7 villages. The collected samples were analyzed for physico-chemical parameters and potentially toxic element i.e. As. The As concentrations were determined by atomic absorption spectrometer (AAS, PG-9900). The overall mean pH values were ranged from 7.41 to 7.91 <7.68 ±0.12>. The lowest mean pH value was that of Dabkot (7.41 ±0.08) while highest mean value was recorded for Azam Warsak (7.91 ±0.15). The pH values were found within the permissible limits of world health organization (WHO) and national quality standards (NEQS). The overall mean values of electrical conductivity (EC) were ranged from 453.71 µs/cm to 806.43 µs/cm <574.65 ±32.55 µs/cm > was found different for each site i.e. the mean value of EC of Kalosha was 574.65 ±36.34 µs/cm which was the lowest one while Azam Warsak was the highest with the mean value electrical conductivity 806.43 ±35.27 µs/cm. The mean values of arsenic concentrations were ranged from 381.93 µg/l to 638.55 µg/l <498.51 ±184.85 µg/l> of the target villages. The highest mean value of arsenic concentration was that of Dabkot (638.55 ±201.49 µg/l) while the lowest mean value (381.93 ±174.88 µg/l) was recorded for Ghangi Khel. Overall insignificant variation in at $p \leq 0.05$ was found among the As concretions of different villages. While the concentrations of As found at the selected villages were well above the permissible limits of WHO and NEQS (10 µg/l). Whereas, the hazard quotient (HQ >1) values were found above 1 that suggested adverse health impacts. It was concluded from the data that the drinking water of the mentioned villages are contaminated with As thus, pose human health risk.

Keywords: Arsenic contamination; Drinking water quality; Human health risk; South Waziristan; Hazard quotient

Assessment with Sustainable Solutions for Water Resource Management in Gwadar: An Evidence-Based Analysis of Challenges and Opportunities

Shafi Muhammad[1,2*], Faisal Hussain[2], Muhammad Aleem Zahid[1], Ahmed Shah[3,4], Zubira Jalil[1], Shereen[5], Komal Tariq[1], Samreen Kher[1]

[1]Faculty of Marine Sciences, Department of Marine Geology, Lasbela University of Agriculture Water and Marine Sciences, Uthal, Pakistan; [2]School of Earth Science and Resources, State Key Laboratory of Geological Processes and Mineral

Resources, China University of Geosciences, Beijing, China; [3]Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan; [4]School of Earth and Space Sciences, University of Science and Technology of China; Faculty of Land Resource Engineering, Kunming University of Science and Technology, Kunming 650093, China; [5]Department of Microbiology, University of Balochistan, Quetta
[*]Email: geoshafi@yahoo.com

Gwadar district, a rapidly developing port city in southern Balochistan, Pakistan, faces significant challenges in sustainably managing its groundwater resources among increasing urbanization and industrialization. Irregular pumping patterns and a lack of detailed aquifer knowledge complicate the management of the freshwater aquifer. This study utilizes detailed geophysical surveys, specifically Vertical Electrical Sounding (VES), and resistivity survey modelling tools to explore groundwater resources widely. Hydrogeological studies in Gwadar and its neighboring areas have identified several zones with significant freshwater aquifers. These aquifers, mainly composed of sandy clay and clayey sand, contrast in groundwater yield due to alterations in porosity and permeability. However, coastal areas face challenges like saltwater intrusion, that affects freshwater quality. Moreover, the drainage patterns indicate that the majority of the aquifer is recharged by rainfall and nearby rivers. The study identifies sustainable solutions, including freshwater conservation measures, integrated water resource management strategies, and policy interventions to address the water resource challenges in Gwadar. By implementing these solutions and utilizing geophysical surveys, Gwadar can secure a resilient and sustainable water future, supporting its socioeconomic development goals.

Keywords: Gwadar; Groundwater; Drainage patterns; Hydrogeological studies; Vertical electrical sounding (VES)

Integration of Community-Based Flood Risk Assessment Using Stakeholder Analysis and Hydrodynamic Modelling

Farazeen Khizer, M. Atiq Ur Rehman Tariq[*], Abdullah Nadeem, Asma Azad

Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore 54890, Pakistan
[*]Email: atiq.tariq@gmail.com

Flooding remains one of the most disruptive and frequently occurring hazards posing challenges forrisk assessment and disaster management. The hazard-based assessments focused mainly on spatialexposure undermine the significance of areas where the impacts of floods are more critical. This studycombines the HEC-RAS 2D simulation of 100-year food event using a design discharge of 102,464cusecs, derived from Historical daily discharge data at Ravi Syphon gauge station, with a PCA BasedSocial vulnerability index developed from household survey conducted in Park View City, LahorePakistan. The results show that mean flood depth and SoVI produced different risk priorities across 15comparable blocks, with an average variation of 43.6 % between them. Tulip block recorded thehighest mean flood depth of 2.44 m, but its integrated priority decreased by 69% due to its low SoVIvalue of

0.204, whereas Diamond block showed a 45% increase in priority where high flood depth of2.25 m coincided with elevated SoVI of 0.713. These shifts show that the integrated approachidentifies not only areas of severe flooding, but also areas where flood impacts are likely to beintensified by vulnerable community conditions. By combining hydraulic and vulnerability layers, thestudy provides practical basis for tracing at-risk communities where the social factors play significantrole besides physical hazard mapping. Risk mapping developed through this approach can guide theinstitutions for proper and productive mitigation, early warning and recovery support strategies for theflood affected areas where assistance is more required than others.

Keywords: Integrated flood risk assessment; HEC-RAS 2D; Social Vulnerability Index (SoVI); Principal Component Analysis (PCA); Community-based vulnerability; Flood hazard mapping

Machine Learning for Spatial Prediction of Fluoride Contamination in Groundwater

Nabeel Afzal Butt[1*], M. Younis Khan[1,2], Seema Anjum Khattak[1], Liaqat Ali[1]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]Department of Earth Science, Sultan Qaboos University, Muscat 123, Oman

[*]Email: nabeel.qau1@gmail.com

Sustainable groundwater management is crucial for safe drinking water in fluoride-affected regions. This study develops a machine learning framework to classify groundwater fluoride using physicochemical predictors. Key features were identified through hydrogeochemical, spatial, and SHAP-based analysis. Model performance was evaluated using nested cross-validation and validated with an independent geology-informed spatial holdout dataset. Multiple machine learning algorithms were tested, including Decision Tree, Support Vector Classifier, Logistic Regression, Gaussian Naïve Bayes, XGBoost, and K-Nearest Neighbours. The Support Vector Classifier outperformed other models, achieving an accuracy of 0.75 and an AUC of 0.821 on the independent spatial test set. The generated prediction maps effectively identify fluoride-prone zones, providing a practical tool for groundwater management, risk mitigation, and sustainable planning in water-stressed regions. This study also supports Sustainable Development Goal 6 by contributing to improved water quality and sanitation strategies.

Keywords: Fluoride contamination; Machine learning; Support Vector Classifier; Hydrogeochemistry; Spatial prediction; Sustainable development

Machine Learning-Based Assessment of Hydrological Drought across the Upper, Middle, and Lower Indus River Reaches

M. Irfan[1], M. Atiq Ur Rehman Tariq[1], M. Waseem[1,2], Mudassar Iqbal[1*], K. Ahmad[1]

[1]Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Lahore, Pakistan; [2]College of Hydrology and Water Resources, Hohai University, Nanjing, China

*Email: mudassar@cewre.edu.pk

Hydrological drought is a critical event that severely affects surface and groundwater resources, particularly in regions like the Indus River Basin. This study investigates hydrological drought across the upper (Besham Qila), middle (Guddu), and lower (Kotri) reaches of the Indus River using machine learning models, including Support Vector Machines (SVM) and Artificial Neural Networks (ANN). Daily streamflow data were utilized to calculate Standardized Drought Indices (SDI and SDHI) for drought assessment, covering training (1991–2004), evaluation (2005–2013), and prediction periods (2014–2020 for Guddu and Kotri, and 2014–2015 for Besham Qila). The models were evaluated through statistical performance indicators, including RMSE, RSR, PBIAS, R^2, and NSE. ANN demonstrated strong performance at Besham Qila ($R^2 = 0.79$) and Kotri ($R^2 = 0.84$), while SVM excelled at Guddu (RMSE = 0.84, $R^2 = 0.89$). SVM performs better at Guddu because of localized differences in hydrology and data patterns, even though the overall climate and models are similar to Kotri. Guddu's data showed simpler, more linear relationships that align with SVM's strengths, while Kotri's complex, and non-linear patterns favor ANN. Factors like flow consistency, data quality, and upstream location influence at Guddu create stable conditions, allowing SVM to perform effectively. The study highlights the potential of machine learning in predicting hydrological drought and offers a more accurate understanding of water scarcity patterns. These findings emphasize the need for integrating advanced machine learning techniques into drought management strategies to mitigate the impacts of climate variability on water resources in the Indus River Basin.

Keywords: Indus River; Hydrological drought; Machine learning; SVM; ANN

Pollution Status and Health Risk Assessment of Heavy Metals via Consumption of Surface and Groundwater of Dir-Kohistan, Khyber Pakhtunkhwa, Pakistan

Shafiullah*, Seema Anjum Khattak, Mohammad Tahir Shah, Liaqat Ali

National Centre of Excellence in Geology, University of Peshawar, Peshawar
Email: shafi4pk100@yahoo.com

Anthropogenic and geogenic inputs to freshwater systems can elevate concentrations of major ions and trace metals, creating chronic exposure pathways that threaten community health. To characterize these risks in Dir Kohistan, we conducted a systematic assessment of physicochemical parameters, major ions, and heavy metals in surface water (SW) and groundwater (GW), and performed a screening human health risk assessment for local residents. Water samples were analyzed following standard analytical protocols and compared against WHO, US EPA, and Pak EPA guideline values. Most routine physicochemical parameters were within guideline limits; however, nitrate exceeded the US EPA drinking water limit in 3.51% of GW samples. Total hardness surpassed the WHO/US EPA threshold (< 300 $mg \cdot L^{-1}$) in 34.09% of SW and 66.67% of GW samples. Major cations (Na, K, Ca, Mg) and trace elements (Mn, Cu, Cr, Ni, Zn, Co) were generally within permissible

ranges, whereas Fe concentrations exceeded guideline values in 81.82% of SW and 56.14% of GW samples. Pb concentrations exceeded the Pak EPA limit (≤ 50 $\mu g \cdot L^{-1}$) in 63.64% of SW and 38.60% of GW samples. Cd exceedances were notable: relative to the US EPA guideline (5 $\mu g \cdot L^{-1}$), 38.64% of SW and 1.75% of GW samples were above the limit; using the more stringent WHO limit (3 $\mu g \cdot L^{-1}$) increased these proportions to 68.18% (SW) and 12.28% (GW). Hazard quotient (HQ) calculations identified Pb and Cd in surface water as primary concerns for ingestion exposure. Although mean hazard indices (HI) for both SW and GW were below 1, maximum HI values exceeded 1, indicating that consumption of certain local water sources may pose non cancer health risks to residents. These findings call for targeted monitoring, source identification, and mitigation measures, particularly for Pb, Cd, and Fe in surface waters, to reduce exposure and protect public health.

Keywords: Surface water; Groundwater quality; Heavy metals; Human health risk assessment; Lead contamination; Cadmium contamination; Dir Kohistan

Spatial Distribution and Hydrological Controls of Microplastic Contamination in Soil and Surface Water of a Mountain-Influenced Watershed, Abbottabad Region, Pakistan

Bushra Zia Khan[1,2*], Rahib Hussain[1,3*], Abdul Qadir[1]

[1]College of Earth and Environmental Sciences, University of the Punjab, Lahore 54590, Punjab, Pakistan; [2]Centre for Integrated Mountain Research (CIMR), University of the Punjab, Lahore 54590, Punjab, Pakistan; [3]Sustainable Development Study Centre, Government College University Lahore

[*]Email: bushra.cimr@pu.edu.pk; dr.rahib@gcu.edu.pk

Microplastic contamination is increasingly recognized as a critical environmental issue in terrestrial and freshwater systems, yet its occurrence, spatial variability, and hydrological controls remain poorly understood in northern Pakistan. This study investigates the abundance, characteristics, and spatial distribution of microplastics in surface soils and connected surface waters within the Abbottabad region, with particular emphasis on the role of land use, topography, and watershed connectivity in shaping contamination patterns. Representative soil and water samples were collected from urban, peri-urban, agricultural, and recreational locations across a mountain-influenced watershed. Microplastics were isolated using density separation and filtration techniques, visually characterized under microscopy, and polymer types were verified using FTIR spectroscopy. Geographic Information System-based analysis was employed to examine relationships among microplastic abundance, drainage pathways, slope, land cover, and proximity to roads and settlements, while statistical analyses were used to test spatial and environmental differences among site categories. The results indicate that microplastic loads in water were 89-265 MPs/L in 2023, while 52-264 MPs/L in 2024. The maximum deposition was observed at Ayubia track, i.e., 265 MPs/L, while the minimum was observed at Khanspur 89 MPs/L (2023), and Bara Gali 52 MPs/L (in 2024), which were attributed to polyvinyl acetate (PVA). Similarly, in soil, the

maximum extent of microplastics (MPs/g) was observed in Ayubia track (89 count), followed by Changa Gali (81 count), Lalazar (72 count), Nathia Gali (51 count), and Namli Maira (38) attributed with various polymeric materials. The spatial distribution and abundance are elevated in hydrologically connected and densely disturbed landscapes, dominated by fibre and fragment particles. Spatial clustering suggests that anthropogenic pressure (vehicles, packaging materials, plastic containers, and inadequate waste management practices), runoff convergence, and local drainage structure play important roles in contaminant accumulation and redistribution. The study provides baseline evidence for terrestrial and freshwater microplastic contamination in a data-scarce region and demonstrates the value of integrating field sampling, laboratory spectroscopy, and geospatial analysis to support watershed-scale pollution monitoring, climate-resilient environmental management, and future risk assessment frameworks.

Keywords: Microplastic contamination; Freshwater pollution; FTIR spectroscopy; Watershed analysis; Abbottabad region

Scoping Environmental Impact Assessment of a Proposed Residential Development at Putteridge Bury, Luton: Integrating Heritage, Ecology, Landscape, and Sustainable Planning Considerations

Rehman Khan[1], Muhammad Shahab[2*], Fahad Alshehri[2]

[1]Environmental Management and Sustainability, University of Bedfordshire, United Kingdom; [2]Abdullah Alrushaid Chair for Earth Science Remote Sensing Research, King Saud University, Saudi Arabia

[*]Email: mshahab.c@ksu.edu.sa

This study presents a scoping-level Environmental Impact Assessment (EIA) for a proposed 51-unit residential development at Putteridge Bury, University of Bedfordshire, Hitchin Road, Luton. The proposed development occupies approximately 2 hectares within a sensitive peri-urban landscape containing a Grade II registered park and garden, heritage assets, mature vegetation, agricultural land, and campus infrastructure. The purpose of the study is to identify the likely significant environmental effects of the proposed scheme, determine the key issues that require detailed assessment in the Environmental Statement, and recommend mitigation priorities before detailed planning and design stages. The assessment adopts an evidence-led scoping framework based on desk studies, mapped constraints, site observations, planning policy review, and receptor sensitivity analysis. Particular attention is given to ecology and biodiversity, landscape and visual effects, transport and access, noise and vibration, air quality, flood risk and drainage, ground conditions, cultural heritage, socio-economic effects, climate resilience, and cumulative impacts. The findings indicate that the south-western edge of the Putteridge Bury boundary represents the comparatively least environmentally intrusive development option because it is closer to existing urban and campus infrastructure, more visually contained by established vegetation, and less

intrusive than central estate or north-eastern open-land alternatives. However, the site remains environmentally sensitive due to its parkland setting, ecological connectivity, heritage value, drainage implications, and potential construction-related disturbance. The study concludes that ecology, landscape character, heritage setting, transport, drainage, air quality, noise, and ground conditions should be fully scoped into the Environmental Statement. Key recommendations include habitat and bat surveys, arboricultural assessment, landscape and visual impact assessment, sustainable drainage design, transport and access appraisal, construction environmental management planning, heritage desk-based assessment, and cumulative impact screening. The scoping exercise demonstrates that residential development at Putteridge Bury may be feasible only if guided by a least-harm design strategy, strong biodiversity protection, sensitive landscape integration, sustainable drainage, and robust construction-phase controls.

Keywords: Environmental impact assessment, EIA scoping, Residential development, Putteridge bury, Luton; Heritage landscape

Ecological and Human Health Risk Assessment of Potentially Toxic Elements in Agricultural Soils and Weathered Sediments of District Swabi, Khyber Pakhtunkhwa, Pakistan

Muhammad Tariq*, Seema Anjum Khattak, Liaqat Ali

National Centre of Excellence in Geology, University of Peshawar, Peshawar
**Email: muhammadtariq332@gmail.com*

In the present study, concentration, distribution, ecological effect and potential health impacts of PTEs in agriculture soils and weathered sediments of District Swabi of Khyber Pakhtunkhwa (KP) Pakistan have been evaluated. Standard sampling procedures were followed to collect samples from all over the study area. Laboratory analyses were carried out to determine physicochemical properties and elemental concentrations through Atomic Absorption Spectroscopy (AAS). The relationships between variables were explored and possible sources of contamination identified using statistical techniques, such as Principal Component Analysis (PCA). The degree of contamination was evaluated using different environmental pollution indicators, such as: Enrichment Factor (EF), Contamination Factor (CF), Geoaccumulation Index (Igeo) and Pollution Load Index (PLI). An exposure assessment model was used and validated for adults and children to estimate ecological and human health risks. Analytical results indicated that the presence of PTEs in the examined soils and sediments is related with lithogenic processes and anthropogenic activities. The multivariate analyses showed that the elements Hg, Mn, Ni and Pb were the most important factors causing elemental variation, whereas EC, TDS and Zn also had a significant influence. The pollution indices computed showed high levels of enrichment of some of the elements, indicating moderate to severe contamination in various areas, exceeding SEPA 2018 guideline values. The most critical contaminants (unpolluted to moderately polluted) were identified as Hg and Cd by the geoaccumulation assessment, while most other

elements were in the unpolluted to moderately polluted range. Generally, the ecological risk assessment results indicated low levels of risk for most of the PTEs, with relatively high levels of concern for Hg and Cd. Human health risk assessment showed that children were more vulnerable to non-carcinogenic effects than adults due primarily to their oral ingestion route of exposure. Additionally, some locations had Cr and Ni concentrations that were above the acceptable limits for carcinogenic risk. The results of the present study emphasize the need for ongoing environmental monitoring and management plans in order to reduce contamination and potential health risks in the area.

Keywords: Potentially toxic elements; Soil contamination; Ecological risk assessment; Human health risk

Geochemical Characterization of Floodplain Soils and Waters: Cadmium and Lead Contamination in Charsadda, Pakistan

Seema Anjum Khattak*, Farhia Baber, Muhammad Tariq

National Centre of Excellence in Geology, University of Peshawar, Peshawar

**Email: s_anjum@uop.edu.pk*

The catastrophic 2010 flood in Pakistan profoundly altered the environmental and geochemical characteristics of agricultural soils in Charsadda District. This study investigates flood-induced changes by comparing floodplain soils and waters with non-flooded control sites. Charsadda's fertile alluvial deposits of Pleistocene age provide a critical agricultural base, making soil quality assessment essential. Soil samples were collected at two depths (0–10 cm and 15–20 cm) and analyzed for pH, electrical conductivity, major oxides, and heavy metals, while water samples were tested for physicochemical parameters and anions. Analytical techniques included aqua regia digestion with atomic absorption spectrophotometry (PerkinElmer AAnalyst 700) and electrochemical analysis for water quality. Results indicate that soil pH and electrical conductivity remain within acceptable ranges, while water parameters largely comply with WHO (2004) and USEPA standards. However, heavy metal concentrations reveal significant flood-related enrichment. At 0–10 cm depth, cadmium (2.95 mg/kg) and lead (1.83 mg/kg) dominate, followed by copper, cobalt, zinc, nickel, chromium, and silver. At 15–20 cm depth, cadmium (4.14 mg/kg) again exceeds safe limits, with lead and cobalt showing elevated values relative to controls. In water, cadmium (75.7 µg/L), lead (37.4 µg/L), and copper (20.27 µg/L) exceed contamination thresholds, highlighting potential ecological and health risks. Geostatistical analysis reveals significant correlations among metals across depths, suggesting common sources and mobility patterns. Spatial mapping identifies hotspots of contamination along floodplains, underscoring the persistence of flood impacts. The findings demonstrate that cadmium contamination in both soil and water is of particular concern, with implications for food safety and public health. While most parameters remain within regulatory limits, the elevated cadmium and lead concentrations necessitate further detailed investigation and long-term monitoring. This study emphasizes

the need for integrated geochemical and environmental management strategies to mitigate flood-induced soil contamination in vulnerable agricultural regions.

Keywords: Drinking water contamination; Potentially toxic metals; Health risk; Rural areas

Source Apportionment and Health Risk Assessment of Potentially Toxic Elements (PTEs) in Water Sources of District Swabi, Khyber Pakhtunkhwa, Pakistan

Muhammad Tariq*, Seema Anjum Khattak, Liaqat Ali, Fakhri Alam

National Centre of Excellence in Geology, University of Peshawar, Peshawar
**Email: muhammadtariq332@gmail.com*

Water samples from District Swabi, Khyber Pakhtunkhwa, Pakistan, were analyzed to determine the concentration of potentially toxic elements (PTEs) and evaluate associated human health risks. A total of 18 surface water (SW) and 126 groundwater (GW) samples were collected from different drinking water sources and analyzed for physicochemical parameters and PTEs including As, Cd, Co, Cu, Fe, Mn, Ni, Pb, and Zn. The results were compared with World Health Organization (WHO) drinking water guidelines. Physicochemical analysis showed that a significant proportion of water samples were unsuitable for drinking purposes. The pH exceeded WHO permissible limits in 44.45% of SW and 52.38% of GW samples, while electrical conductivity exceeded the acceptable limit (400 µS/cm) in 66.67% of SW and 27.78% of GW samples. Among the analyzed PTEs, Cu, Cr, and Ni remained within safe limits, whereas serious contamination was observed for As, Cd, Pb, and fluoride (F^-). Arsenic contamination was detected in 72.2% of SW and 62.7% of GW samples, while Pb exceeded WHO limits in 66.6% of SW and 50% of GW samples. Cadmium was identified as the most critical contaminant, with 100% of both SW and GW samples exceeding the WHO permissible limit (5 µg/L). Similarly, fluoride contamination was observed in 55.6% of SW and 78.6% of GW samples. Overall, groundwater was found highly contaminated with Cd, As, F^-, and K, while surface water was also unsuitable for safe consumption. Health risk assessment revealed that the chronic daily intake (CDI) values in SW followed the order Fe > Ni > Mn > Co > Cu > Pb > Cr > Cd > As > Hg, whereas in GW the order was Fe > Ni > Co > Mn > Cu > Pb > Cr > Cd > As > Hg. Hazard quotient (HQ) values greater than 1 for As, Co, and Cd indicated significant non-carcinogenic health risks associated with water consumption. Furthermore, hazard index (HI) values exceeding 1 for both adults and children suggested that long-term consumption of contaminated water may lead to adverse health effects, particularly among children. Multivariate statistical analyses indicated that both geogenic and anthropogenic activities contributed to groundwater and surface water contamination in the study area.

Keywords: Potentially toxic elements; Health risk assessment; Source apportionment; Statistical analysis

Status of Fluoride and Nitrate Distribution in the Soils of District Mardan, Pakistan

Bushra Khan[1], Zia ur Rahman[2*], M. Ayaz Khan[2], M. Khurshid[2] , Nida Gull[3]

[1]Department of Environmental Sciences, University of Peshawar, KP; [2]Department of Environmental Sciences, The University of Haripur, Haripur 22620, KP, Pakistan; [3]Department of Environmental Sciences, University of Swabi, KP

[*]Email: zia@uoh.edu.pk

In order to predict the Fluoride (F^-) and Nitrate (NO_3^-) leaching capacity, soil samples (n = 96) were collected at four different depths from agriculture fields while the estimated amount of fertilizer load was collected from farmers. Soil samples were analysed for physicochemical data on parameters like texture, bulk density, particle density, organic matter (OM), pH, electric conductivity (EC). Anions like fluoride (F^-), nitrate (NO_3^-), nitrite (NO_2^-), chloride (Cl^-), bromide (Br^-), phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}) were determined through Ion Chromatography (IC) while cations like Na^+, K^+, Ca^{2+}, Mg^{2+} and Al^{3+} were determined using Inductively-Coupled Plasma Mass Spectrometry (ICP-MS). Most of the samples were found to be alkaline with pH range from 7.60 to 8.37 and the dominant soil texture was silt followed by sand and clay. Organic Matter (OM) ranged between 0.91%–1.52%. Pandehri Bala (Mardan) recorded the lowest F^- (0.33 mg/kg), while Butseri showed the highest (4.24 mg/kg). Mean NO_3^- levels were 12.06 mg/kg (Katlang), 23.32 mg/kg (Mardan), 22.98 mg/kg (Rustam), and 18.31 mg/kg (Takht Bhai). Unlike F^-, the concentration which was found in increasing order with depth, NO_3^- was found in decreasing order with the increasing depth. Samples collected from Alo village in Katlang and Palu Dehri Rustam showed minimum (3.83 mg/kg) and maximum (35.93 mg/kg) average concentrations of NO_3^-, respectively. Depth-wise analysis of soil indicated that F^- has been added by the natural rocks, while NO_3^- could be attributed to excessive application of synthetic nitrogenous fertilizers. Regardless of fertilizer application rates, soils in Mardan and Katlang retain more NO_3^-, posing lower groundwater risk, whereas Mardan and Rustam soils show higher water-soluble F^- levels. Therefore, regular monitoring of agricultural soils for inorganic anions, particularly NO_3^- and F^-, is essential to mitigate potential risks to public health.

Keywords: Soil contamination; Fertilizer loading; Ion chromatography; ICP-MS; Agricultural soils

The Effect of Microbial Formulation on *Taxus wallichiana* (Himalayan Yew) Seedlings and Soil Conditions

Samina Siddiqui[1*], Sanam Zarif Satti[1,2]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]Pakistan Forest Institute (PFI), Peshawar
[*]Email: samina@uop.edu.pk

Taxus wallichiana (Himalayan yew) (TW) nursery stock is rapidly disappearing due to human-induced climate change. Therefore, it is necessary to conserve such a nursery by adopting biological techniques. The role of microbes in accelerating TW nursery growth has rarely been reported. The present study aims to evaluate the beneficial effects of microbes on TW seedling growth and soil conditions. The objectives of this study were to prepare a microbial formulation for TW nursery growth, to assess its antioxidant potential, and to evaluate its effects on other soil conditions. For that purpose, a greenhouse experiment was conducted at the Pakistan Forest Institute in Bhurban-Murree. *TW* small seedlings were collected from the moist temperate forest in Murree and were planted in 9 pots (with 3 replicates of each, control, with *pseudomonas pseudomonas granadensis* (PG) PZ159268 and *perrybacillus frigoritolerans* (PBF) PZ159266). Each microbe was mixed with 500g of autoclave and non-autoclave soil and TW seedlings were sown. After 75 days of inoculation soil and TW leave samples were taken and were analyzed for soil pH, total nitrogen, phosphorus and potassium, organic matter and antioxidant potential. Seedlings length was increased with PBF from 15 to 30.48cm and with PG 13cm to 24.36cm than control. Similarly branch length and numbers of branches and leaves were two folds more in TW seedlings with PBF than PG and three folds than control without PBF and PG. Organic matter content increased from 2.7% to 3.1% in soil with PBF and PG than control. Antioxidant potential (DPPH%) and Superoxide Dismutase (SOD) increased with PBF, and Peroxidase (POD) and Ascorbate Peroxidase (APX) was same in PBF and PG than control. This suggests that PBF has a more profound effect on TW seedling physiology, antioxidant potential, and soil conditions. Future research should focus on optimizing the use of microbial formulations for different plant species and soil types to maximize their benefits.

Keywords: *Taxus wallichiana*; Microbial inoculation; Plant growth promotion; Soil fertility; Antioxidant enzymes

Eco-Climate Refugia Identification in High-Mountain Ecosystems of Gilgit-Baltistan under Climate Change

Fatima Nazir Ali[1*], Aqsa Shabbir[2], Sahar Zia[1]

[1]Department of Geography, Lahore College for Women University, Lahore 54000, Pakistan; [2]Department of Electrical Engineering, Lahore College for Women University, Lahore 54000, Pakistan

[*]Email: fatimanazirali.786@gmail.com

Climate change poses severe threats to mountain forest ecosystems, particularly in high elevation regions with complex topography. This study identifies and maps eco-climate refugia-areas of climatic stability and ecological persistence in the mountainous forests of Gilgit-Baltistan, Northern Pakistan, within the Himalayan–Karakoram– Hindukush Mountain system. These refugia serve as potential long-term habitats for forest species under changing climatic conditions. The research integrated multi-temporal geospatial datasets, including MODIS Land Surface Temperature (LST) and NDVI time series (2010–2025), 30 m SRTM/ASTER Digital Elevation Model, CHIRPS rainfall records, and forest cover data from Global Forest Watch and ESA World Cover. All datasets were preprocessed in Google Earth Engine and ArcGIS. Thermal stability was quantified using the interannual standard deviation of LST, while vegetation persistence was evaluated through NDVI trend and fluctuation analysis. Topographic buffering capacity was derived from elevation, slope, aspect, and Terrain Ruggedness Index (TRI). Rainfall stability was assessed via long-term precipitation variability. These layers were integrated using Multi- Criteria Suitability Modeling (MCSM) through weighted overlay analysis in ArcGIS Pro, with assigned weights: Thermal Stability (30%), Vegetation Persistence (25%), Elevation Buffering (20%), Rainfall Stability (15%), and Forest Density (10%). The study produced high-resolution maps classifying the region into high-resilience refugia, moderate refugia, and vulnerable forest zones. Validation was performed through cross-comparison with existing protected areas and historical forest persistence data. This research provides the first comprehensive geospatial delineation of eco-climate refugia in Gilgit-Baltistan, offering valuable insights for climate adaptation planning, biodiversity conservation, protected area prioritization, and sustainable forest management in this climate-sensitive mountain region.

Keywords: Eco-climate refugia; Climate change adaptation; GIS multi-criteria analysis; Gilgit- Baltistan forests; NDVI and MODIS LST

Theme 8: Sedimentology, Palaeontology, Mineralogy & Petrology

Textural, Geochemical, and Mineralogical Evaluation of Silica Sand of the Nari Formation and Recent Deposits, Malmari Area, District Jamshoro, Sindh, Pakistan

Muhammad Hassan Agheem*, Aijaz Ali Halipoto, Abdul Jabbar Talpur, Akhtar Hussain Markhand

Centre for Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan
**Email: mhagheem@usindh.edu.pk*

The quartz-rich loose sand size particles are known as Silica Sand. It is a vital raw material used for diverse industrial applications, particularly for glass manufacturing, solar industries, semiconductor, ceramics, foundries, and other silica-based industries. Although Pakistan hosts significant silica sand reserves in different regions, which are being used for various purposes but detailed investigations of the silica sand of Nari Formation of Oligocene age and Recent deposits in the Malmari area, district Jamshoro have not previously been conducted. For last so many years, the silica sand of Nari Formation is being used by local industries in Karachi but the literature survey indicates that no detailed studies have been carried out yet. Therefore, the current research is carried out to evaluate the textural, geochemical and mineralogical composition of these sand deposits for various industrial applications. Total 22 loose sand samples (NRM-1 to NRM-22) were collected from Nari Formation and Recent Deposits of the Malmari Area, district Jamhoro, Sindh. Out of 22 samples, 19 samples were selected for the sieve-based grain size analysis (both unwashed and washed samples) and 10 selected samples were analyzed for XRF, SEM & EDS and then petrographic examination under a Zoom stereo microscope. Results reveal that grain size is medium to fine, grain shape is sub angular to sub rounded, with moderate sorting and depositional environment is fluvial to wave dominant. Geochemical analysis reveals that the dominant mineral phase is quartz but other iron oxides and carbonates are also present. Overall results indicate that the silica sand of the Malmari Area can be used for different industrial purposes after beneficiation or up gradation techniques to remove the impurities through different mineral processing methods.

Keywords: Silica sand; Nari Formation; Industrial minerals; Geochemical analysis; Malmari Jamshoro

Hangu Coal Extension: Updated Correlations of Hangu, Coal-Bearing and Non-Coal Patala, Panoba, and Nammal Formations of the Upper Indus Basin, Pakistan

M. Sadiq Malkani

Geological Survey of Pakistan, Quetta/Islamabad, Pakistan
**Email: malkanims@yahoo.com*

Early Paleocene Hangu Formation is the main coal producer in the upper Indus basin (Kohat-Potwar-Kotli-Muzaffarabad basin) of Pakistan. These coal deposits and their extension are significant for source of energy and critical minerals (rare earth elements and other associated minerals in coal ash and inorganic constituents). Hangu coal exposures are found in the northern thrust of Kohat-Potwar-Muzaffarabad foldbelt (Main Boundary thrust/MBT) and southern thrust of Kohat-Potwar-Kotli foldbelt (Salt Range thrust) regions. MBT is a boundary between uppermost Indus (Khyber-Hazara-Neelam) basin and upper Indus (Kohat-Potwar-Kotli-Muzaffarabad) basin. MBT is not a single thrust but it is repetition of many thrusts, for example in Cherat Range of Nowshera district it is represented by Dara Adam Khel and Kohat thrusts and in the western extremity areas fall under territory of Kohat, Hangu, Orakzai, Kurram and Khyber districts of Khyber Pakhtunkhwa/KP which hosts seven thrusts named as Dara Adam Khel, KDA Kohat, south western Kohat city, Samana, Spinkai, Darsamand and Khadimak anticlinal thrusts with Jurassic core strata as Datta (host of diplodocid dinosaur), Shinawari and Samanasuk Formations. The southern side of these anticlinal thrusts have thrust fault, while northern sides represent folded Cretaceous and Early Paleocene strata also hosting the coal bearing Hangu Formation which is partially exposed and partially covered, partially easy and partially difficult accessibility due to rugged higher elevations and security problems. Hangu coal is being mined from Hangu, Orakzai, Kohat, Karak, Nowshera and Abbottabad (and possibly Haripur) districts of KP, Muzaffarabad and Kotli districts of Azad Kashmir, and Mianwali, Khoshab, Talagang, Chakwal and Jhelum districts of Punjab. Further Hangu coal extension is expected in lower and upper parts of Orakzai district, eastern part of Kurram district, Kohat Ranges located in the northern part of Kohat district, eastern part of Haripur district, Tirah Range and southern parts of Khyber district. Hangu Formation consists of shale, sandstone, and coal in the western part, while sand is decreasing in the east part of upper Indus basin. The Hangu Formation is correlated with (and lateral extension of) the Patala Formation (coal bearing) in other areas and the Salt Range of upper Indus basin. Panoba Formation is correlated with (and lateral extension of) the non-coal Patala Formation in the Kohat sub basin especially in its northern part. Nammal Formation is correlated with (and lateral extension of) the non-coal Patala Formation (Potwar sub-basin) including Kotli and Muzaffarabad regions. The Panoba Formation (Kohat sub-basin) is correlated with (and lateral extension of) the Nammal Formation (Potwar sub-basin) and adjoining Kotli and Muzaffarabad regions. Coal bearing Patala Formation is a junior synonym of

Hangu Formation, while non-coal Patala Formation is junior synonym of Panoba Formation in Kohat sub-basin and Nammal Formation in Potwar sub-basin and adjoining Kotli and Muzaffarabad regions.

Keywords: Hangu Formation; Coal deposits; Upper Indus Basin; Main Boundary Thrust; Rare earth elements

Oligocene Carbonate Platform Evolution in the Southern Indus Basin, Sindh, Pakistan

Surriya Bibi Ahmedani[1,2*], Aijaz Ali Halepoto[1], Asghar A. A. D. Hakro[1], Muhammad Hassan Agheem[1], Abdul Shakoor Mastoi[1]

[1]Centre for Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan;
[2]Government Zubeda Girls College, Hyderabad, College Education Department, Government of Sindh, Pakistan
[*]Email: suriyabibi128@yahoo.com

The Oligocene epoch represents a pivotaltime in the geological evolution of the northwestern Indian Plate, particularly within the Indus Basin. During this time, the basinunderwent regional emergence, significant changes in geometry, evolving sedimentation patterns and intense tectonic activity. Much of the Indus Basin either lacks Oligocene sediments entirely, as in the Upper Indus Basin, or preserves only continental deposits, such as the Nari and Chitarwatta Formations of the Lower Indus Basin. Nevertheless, localized marine carbonate deposition persisted in parts of the basin during this epoch. These carbonates are geologically significant, as they represent the final remnants of marine sedimentation in the Indus Basin. Despite their importance, the spatio-temporal depositional evolution of these carbonates remains poorly understood. This study aims to investigate the depositional and diagenetic conditions of these carbonates within the Oligocene Nari Formation in the Karachi Embayment, Southern Indus Basin. The Karachi Embayment is a distinct depositional unit located in the southwestern part of the Indus Basin. The Nari Formation is widely exposed throughout this region and consists of both carbonate and mixed carbonate-clastic units. Outcrop sections of the Nari Formation were measured and sampled from three different areas: the Surjan, Rois and Hundi anticlines. The nature of the lower and upper contacts of the formation was carefully observed in the field to reconstruct basin geometry and accommodation space history. Collected samples were analyzed through petrography and X-Ray Diffraction (XRD) to identify texture, mineralogy and diagenetic features. Field observations shown westward thickening of the Nari Formation from the Surjan section in the east to the Hundi section in the west. This trend suggests that the Oligocene basin was opening and deepened toward the west. The basal contact of the Nari Formation isvariable across the study area.At Hundi section, it conformablyoverliesthe Late Eocene Kirthar Formation. At Rois section, it rests unconformablyon the Early Eocene Laki Formation, while at Surjan section, it unconformably overlies the Middle Eocene Tiyon Formation. This variability in basal contacts records a regionally significant marine transgression event that preceded deposition of the Nari Formation. Petrographic analysis revealed that

the carbonates of the Nari Formation are dominantly composed of mudstone, wackestone and packstone microfacies, with abundant foraminifera and algae. These microfacies are consistent with deposition in a range of shallow-marine environments, from restricted lagoon to open-marine conditions on a carbonate platform. XRD analysis further suggested that the limestone have undergone partial to complete dolomitization. The integrated field, petrographic and XRD data indicate a systematic vertical facies evolution within the formation. The lower part is dominated by dolostone and dolomitic limestone. The middle part dominantly consists of mixed carbonate-clastic sequences, reflecting episodic influx of clastic material onto the carbonate platform. The upper part marks a return to carbonate-dominated sedimentation, characterized by algal limestone. These findings collectively suggest that a westward-opening marine carbonate platform existed in the Southern Indus Basinduring the Oligocene. While the platform was mainly a site of carbonate deposition, it periodically received clastic sediments, reflecting the interaction between tectonic uplift, relative sea-level changes and sediment supply. This study provides new insights into the final phase of marine sedimentation in the Indus Basin and contributes to a broader understating of the tectonic evolution of the northwestern Indian Plate during the Oligocene.

Keywords: Southern Kirthar Fold Belt; Thick-skinned deformation; Fault inversion tectonics; Jurassic extensional faults; Himalayan–Suleiman–Kirthar orogeny; Balanced cross-section

Integrated Spectral and Geochemical Characterization of a Chang'e-5 Lunar Sample Using VNIR-SWIR, pXRF, and SEM-EDS Analyses

Jawad Nasir[1], Khalid Latif[2*], Muhammad Rizwan[2,3], Rahat Ullah[2,4], Hafiz Uzair Ahmed[1], Ayyaz Ameen[1], Ghulam Mustafa[1], Amjad Ali[1]

[1]Space Applications and Research Wing, Pakistan Space and Upper Atmosphere Research Commission (SUPARCO), Pakistan; [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [3]State Key Laboratory of Continental Evolution and Early Life, Department of Geology, Northwest University, Xi'an 710069, China; [4]Geological Survey of Pakistan, Quetta/Islamabad, Pakistan

[*]Email: khalidlatif@uop.edu.pk

This study presents Pakistan's first high-resolution spectral and micro-geochemical characterization of an extraterrestrial material, analyzing a 6 mg Chang'e-5 lunar regolith sample retrieved from Oceanus Procellarum under the CNSA Lunar Sample Loan Program. This collaborative milestone marks a significant entry into planetary spectroscopy, integrating visible-to-shortwave infrared (VNIR–SWIR) spectroscopy, portable X-ray fluorescence (pXRF), and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM–EDS) to constrain the sample's mineralogy, geochemistry, and petrogenesis. Spectral measurements were performed by using a high-resolution spectroradiometer (350–2500 nm) under rigorous contamination controls.

Advanced data processing, isolated a high-quality reflectance spectrum displaying two prominent diagnostic electronic transition absorption features at approximately 1035 nm (Band I) and 2253 nm (Band II). Rather than representing independent mineral phases, the specific coordinate pairing of these bands is fundamentally diagnostic of a matrix dominated by high-Ca augitic clinopyroxene influenced by Fe^{2+} - Ca^{2+} substitution in the expanded crystal lattice. This long-wavelength Band II shift beyond 2250 nm matches the unique clinopyroxene-rich signature reported for Chang'e-5 basalts which represent the youngest volcanic units on the Moon (~2.0 Ga) and distinctly contrasts with older Apollo basalts that exhibit shorter ~2 μm band positions (~2100–2200 nm) due to orthopyroxene-dominated lithologies. Furthermore, the complete absence of hydration features at 1400 nm and 1900 nm rigorously validates the hyper-arid, anhydrous lunar character of the sample, confirming that zero terrestrial atmospheric moisture contamination occurred during laboratory handling. This surface optical behavior is securely anchored by complementary bulk and micro-scale geochemistry. Bulk pXRF results establish a low silicon content of 8.29 wt%, which explicitly confirms the absolute absence of free quartz or silica-saturated phases and rules out any evolved terrestrial or felsic contamination. The bulk profile is further characterized by near-equal Aluminum (5.30 wt%) and Calcium (5.39 wt%) contents, moderate Iron (7.03 wt%), and low Titanium (1.30 wt%), defining a plagioclase-dominated, non–high-Ti basaltic framework. Elevated sulfur (2.50 wt%) chemically points to an accessory phase of troilite (iron sulfide). Highly localized SEM–EDS microanalysis confirms these multi-scale trends, directly identifying anorthitic plagioclase, compositionally zoned Fe-Mg pyroxene, and accessory ilmenite (Fe ~ 33 wt%, Ti ~ 30 wt%). Micro-textural relationships indicate a primary igneous crystallization sequence involving early pyroxene formation followed by plagioclase growth and late-stage Fe–Ti oxide segregation, consistent with a differentiated basaltic achondrite (eucritic) precursor affinity. Subsequent hypervelocity impact processes physically reworked this material, resulting in sub-microscopic brecciation, elemental mixing, and a polymict nature. Ultimately, the alignment of the 2253 nm absorption center within the internationally established index for Chang'e-5 basalts (2200 - 2270 nm) validates the integrity of domestic laboratory protocols and demonstrates that highly valuable, rigorous planetary datasets can be successfully extracted from micro-scale sample masses.

Keywords: Chang'e-5 lunar sample; VNIR–SWIR spectroscopy; pXRF; SEM–EDS; High-Ca clinopyroxene; Basaltic achondrite; Lunar breccia

Petrochemical Investigation of the Utror Metavolcanics Exposed in Upper Dir, Western Kohistan Island Arc, North Pakistan

Israr Ud Din[1*], Liaqat Ali[1], Izaz Aziz[2], Shah Fahad Alam[1], Amjad Ali[1]

[1]National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan; [2]Mineral Testing Laboratory, Mineral Development Department, Khyber Pakhtunkhwa, Pakistan

[*]Email: isrargeo01@gmail.com

The western Utror Volcanics in the Kohistan Island Arc, northern Pakistan, are dominated by andesite and basaltic-andesite, with minor basalt, high-MgO basalt, dacite, and rhyolite. Rocks are mainly porphyritic; plagioclase is the dominant phenocryst in mafic–intermediate types, while quartz and K-feldspar characterize felsic rocks. Metamorphism is characterized by greenschist-facies assemblages (epidote, chlorite, albite, actinolite), with local epidote–amphibolite facies conditions. Geochemical trends show decreasing FeO, MgO, CaO, Al_2O_3, TiO_2, Ni, Cr, V, and Sc with increasing SiO_2, while Ba, Rb, and alkalis increase, indicating calc-alkaline affinity. Trace element patterns display enrichment in Large Ion Lithophile Elements (LILE) and depletion in Niobium (Nb), Titanium (Ti), and Phosphorus (P), consistent with a subduction-related volcanic arc setting. Rare Earth Element (REE) patterns show enrichment in Light Rare Earth Elements (LREE) (Eu/Eu* = 0.4–0.8; La/Lu = 2.4–9.7), indicating pronounced plagioclase fractionation, particularly in dacitic and rhyolitic rocks. Andesites show variable La/Lu ratios and distinct REE trends, suggesting multiple magmatic sources rather than a single parent magma. The dominance of mafic lavas indicates limited continental crust involvement, while evolved melts likely reflect partial melting of lower arc crust, possibly leaving garnet-rich granulitic residues similar to those in the Jijal Complex.

Keywords: Kohistan Island Arc; Utror volcanics; Calc-alkaline magmatism; Subduction-related volcanism; Rare earth elements (REEs); Arc petrogenesis

Provenance, Depositional Environment, and Tectonic Evolution of the Bostan Formation, Pishin Belt, Balochistan, Pakistan

Usman Ghani[1,2], Aimal Khan Kasi[1*], Mohibullah[3], Razzaq Abdul Manan[1]

[1]Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan

[2]Regional Meteorological Centre, 46 Jail Road, Lahore, Pakistan; [3]Department of Geology, University of Balochistan, Quetta, Pakistan

[*]Email: aimal_kasi@yahoo.co.uk

This study investigates the tectonic evolution, depositional environment, and provenance, of the Bostan Formation within the Pishin Belt. The formation comprises mudstone, conglomerate, and sandstone, and is chronologically equivalent to the Lei and Haro conglomerates. Detailed fieldwork included stratigraphic logging and systematic sampling, followed by petrographic and Scanning Electron Microscopy (SEM) analyses. Ten number of lithofacies were recognized and grouped into eight facies associations, reflecting significant spatial variability. Conglomerate-dominated sections at Ghazaband and Surkhab

indicate alluvial fan progradation over delta plain and lacustrine environments. In contrast, mudstone-rich sections at Bostan Railway Station and Yaroo Band China suggest deposition in deltaic to lacustrine settings. Overall, the formation records sedimentation in a lacustrine–deltaic system subjective by low-sinuosity braided channels. Petrographic analysis shows that the sandstones are sub-mature to mature, mainly of lithic fragments, quartz, plagioclase, and K-feldspar, with quartz, calcite, and chlorite as cementing materials. Accessory minerals such as zircon, tourmaline, and rutile further constrain provenance. Conglomerates are poorly to moderately sorted, with well-rounded clasts, indicating derivation from nearby uplifted terrains, including ophiolitic complexes and older sedimentary units. The evolution of the Bostan Formation is closely linked to tectonic processes associated with the convergence between the Indian Plate and the Eurasian Plate, leading to foreland basin development and uplift. This study provides important insights into the tectono-sedimentary evolution of the region and contributes to the understanding of foreland basin systems.

Keywords: Bostan Formation; Pishin Belt; Tectono-sedimentary evolution; Provenance analysis; Foreland basin

Prospectivity of Placer Gold and REEs along the Indus River in Swabi Area: Geomorphological and Stratigraphic Controls

Shah Fahad Alam*, Liaqat Ali, Ihtisham Ullah

National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan

**Email: alam.xad7@gmail.com*

The distribution and concentration of placer gold and rare earth elements (REEs) along the Indus River was investigated in Swabi area of Khyber Pakhtunkhwa, with a focus on the river geomorphology and depositional setting of the sediments. Active channel bars, basal channel-lag deposits, and fluvial terrace sediments were encountered as the three distinct geomorphological and depositional environments. Each environment reflects different energy levels and sediment reworking histories, together providing a more complete picture of how gold and heavy minerals travel, settle, and gradually concentrate within the alluvial system. Active channel bars, formed by seasonal floods and fluctuating currents, keep gold particles mobile and dispersed, thus making them unfavorable for substantial accumulation. In contrast, basal channel-lag deposits, evolved through multiple cycles of scouring and strong mineral sorting, appear to be the most desirable traps for placer gold and heavy minerals concentration. Lower fluvial terraces maintain ancient, reworked sedimentary sequences enhanced by long-term hydraulic winnowing, making them geologically suitable targets. The concentrations of Au and Ag were found to be 1.24 ppm and 0.58 ppm respectively, exceeding typical normal levels. Notably, rare earth elements including cerium (Ce) and lanthanum (La) were recorded in pan concentrate samples, further underlining the broader commercial significance of the study area. Meanwhile, the predominance of fine, flaky gold grains reflects the effects of long transport distances and repeated sediment recycling conditions that work against the preservation of coarser material but allow gold to selectively enrich within structurally and stratigraphically favorable horizons. The results are promising, suggesting real medium-to-significant potential for placer gold and REE exploration in the study area but turning that potential into something commercially meaningful will necessitate further, more focused investigation particularly in stratigraphy, sedimentology, and geochemistry before any firm conclusions can be reached.

Keywords: Placer gold; Rare earth elements (REEs); Indus River; Fluvial geomorphology; Channel-lag deposits; Heavy mineral concentration; Hydraulic winnowing

Non-Linear Threshold Behavior and Anomalous Mechanical Responses of Thermally Treated Himalayan Granites: Evidence from Direct Shear and Triaxial Tests

Abdul Rahim Asif[1]*, Muhammad Sajid[2,3], Waqas Ahmed[1]

[1] National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan

[2] Department of Geology, University of Peshawar, Peshawar 25120, Khyber Pakhtunkhwa, Pakistan

[3] Department of Geology, Abdul Wali Khan University Mardan, Khyber Pakhtunkhwa, Pakistan

**Email: abdulrahimasif@uop.edu.pk*

This study investigates the influence of thermal treatment on the mechanical properties of nine granite specimens from the northwestern Himalayan region of Pakistan. The suite comprises fine-, medium-, and coarse-grained varieties (three replicates each), subjected to isothermal heating at 25°C, 100°C, 200°C, 400°C, 600°C, 800°C, and 1000°C. Post-treatments, specimens underwent direct shear and triaxial compression testing (5–15 MPa confining pressure), complemented by

petrographic and SEM analysis. Results reveal a biphasic mechanical response: initial strengthening from 25°C to 200–300°C, followed by progressive deterioration beyond 400°C. The α-β quartz transition at ~573°C acts as a critical threshold, generating pervasive microfractures through volumetric expansion. Coarse-grained granites show highest thermal susceptibility, while fine-grained varieties exhibit greatest stability. Cohesion increases significantly ($p < 0.05$) up to 300°C due to microcrack closure and enhanced frictional interlocking, then declines sharply post-400°C as thermal mismatch stresses generate new crack networks. The internal friction angle remains stable throughout. Cohesion variation is grain-size dependent: coarse-grained granites show peak-to-trough fluctuations ~4.7× greater than fine-grained types. Peak shear strength peaks at 200–350°C before monotonic reduction. Under low confining pressure, all granites become increasingly brittle at elevated temperatures. Under high pressure, coarse-grained granites transition to ductile failure ≥600°C with strain hardening, while fine-grained granites retain brittle behavior even at 1000°C. Medium-grained granites show intermediate behavior. The elastic modulus decreases monotonically with temperature—modestly (<30%) up to 400°C, severely (>60%) beyond 600°C. At 800°C, modulus reductions reach 54–72% (coarse-grained: ~68%; fine-grained: 38–45% retention). These findings indicate fine-grained granite as most suitable for high-temperature engineering applications. The initial strengthening phase benefits enhanced geothermal systems, while deterioration beyond 600°C poses risks for nuclear waste repositories, underground coal gasification, post-fire tunnel rehabilitation, and geothermal reservoir management.

Keywords: Thermal treatment; Granite; Mechanical properties; Triaxial compression; Direct shear strength; Quartz phase transition; Himalayan granites

Heavy Metal Enrichment and Soil Quality Risks in Agricultural Lands of District Peshawar, Pakistan

Khalid Khan, Said Muhammad*, Wajid Ali

National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan

**Email: saidmuhammad1@gmail.com*

Heavy metal contamination in agricultural soils threatens soil quality, causing ecological imbalance, pose threat to both crop safety, and human health, mainly in areas affected by wastewater irrigation, urban expansion, and increasing pressure on freshwater resources. This research assessed heavy metal enrichment in agricultural soils of District Peshawar, Khyber Pakhtunkhwa, Pakistan, across four different land-use systems: canal-irrigated, industrial wastewater-irrigated, rainfed, and urban agricultural soils. Soil samples were analyzed for Cr, Cd, Cu, Zn, Pb, Ni, Mn, Co, and Fe using atomic absorption spectrophotometry after aqua regia acid digestion, while pH, electrical conductivity, and loss on ignition were used to interpret metal behavior under local soil conditions. Bulk soil data were used to identify land-use controls on metal enrichment and soil quality risk. The results indicate that land use system influenced metal accumulation. The soil sample from industrial wastewater-irrigated soils showed the highest anthropogenic enrichment, especially for Cd, Pb, Zn, and Cu, reflecting the influence of untreated or poorly managed wastewater inputs. Canal-irrigated and urban agricultural soils showed mixed enrichment patterns associated with alluvial sediment supply, agricultural inputs, traffic dust, organic amendments, and peri-urban farming activities. However, rainfed soils generally showed lower anthropogenic influence, although Fe, Mn, Cr, Ni, and Co were mainly controlled by the regional alluvial and geological background. Cd, Pb, and Zn emerged as the most environmentally

significant metals because of their association with wastewater irrigation, urban influence, and agricultural practices. Although climate variables were not directly measured, the findings have implications for climate- sensitive land management. Under semi-arid conditions, changes in rainfall intensity, runoff generation, evapotranspiration, dust activity, and irrigation demand may increase the redistribution of contaminated soil particles across agricultural landscapes. The study provides a baseline for identifying high-risk agricultural zones, improving wastewater monitoring, and integrating soil contamination data into irrigation and runoff-management planning. These findings are relevant not only to Peshawar, but also to other rapidly urbanizing semi-arid agricultural districts of Pakistan and comparable wastewater- affected farming systems worldwide.
Keywords: Heavy metals; Agricultural soils; Wastewater irrigation; Soil contamination; Climate resilience; Peshawar Valley

Assessment of Air Pollution Tolerance Index (APTI) in Vegetation Growing Across Various Land Use Sites

Shahzadi Manan, Naureen Aurangzeb* and Muhammad Ayaz Khan
Department of Environmental Sciences, The University of Haripur, Haripur 22620, Khyber Pakhtunkhwa, Pakistan
**Email: naureen.aurangzeb@gmail.com*

Dust arising from various land use sites contribute significantly in deteriorating air quality and therefore needs regular monitoring and control. For this purpose, plants globally have gained scientists attention. This study was, therefore designed to assess Air Pollution Tolerance Index (APTI) of the studied plants. For this purpose, plants sampling was carried on the basis of their prevalence from selected industrial estate, brick kilns and road sides serving as a potential source of dust pollution in district Haripur, Khyber Pakhtunkhwa-Pakistan. Dust and Black Carbon (BC) deposited on the plant leaves was measured. Selected biochemical parameters were determined to calculate the APTI of the studied plants. Among 15 studied plant species, highest dust deposition was observed in *C. procera*, *Z. mays* and *F. rubiginosa* from brick kiln, industrial and road sites, respectively. Significant difference ($p<0.05$) was observed in BC trapping potential of the plant at brick kiln and road site as compared to industrial site indicating an insignificant difference among the studied sites. Additionally, the accumulated dust showed significant impact ($p<0.05$) on plant biochemical parameters. It was, therefore, concluded that *C. procera* and *E. japonica* from brick kiln site; *F. rubiginosa* and *A. scholaris* showed APTI was found to be ≥17 making them highly tolerant against dust pollution, while *R. communis* from industrial site showed intermediate tolerance against deposited dust. Rest studied plants have been observed to be sensitive towards dust pollution. Thus, *C. procera* and *E. japonica*, *F. rubiginosa* and *A. scholaris* are highly recommended for development of green belt in study area and elsewhere where required.
Keywords: Air pollution tolerance index (APTI); Dust pollution; Black carbon; Green belt development; Industrial emissions; Brick kilns; Haripur Pakistan

Adsorptive Removal of Cationic Heavy Metals Using Surface-Modified Bentonite Clay

Junaid Khalil[1], Shah Rukh[1]*, Ayaz Mehmood[2], Anis Safir[3], Kouser Majeed Malik[4], Syed Ali Turab[1]
[1] National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Khyber Pakhtunkhwa, Pakistan

[2] Department of Soil & Climate Sciences, The University of Haripur, Haripur 22620, Khyber Pakhtunkhwa, Pakistan
[3] Department of Environmental Sciences, University of Peshawar, Peshawar 25120, Pakistan
[4] Soil and Water Testing Laboratory for Research, Rawalpindi 46300, Pakistan
*Email: shahrukh.nceg@uop.edu.pk

In the present work, natural bentonite clay has been investigated for its use in removing the cationic heavy metal ions like lead (Pb), chromium (Cr) and nickel (Ni) from water. The physicochemical parameters (pH, CEC and elements composition) of the samples of the bentonite deposits from local sources in Garhi Chandan area of Khyber Pakhtunkhwa region in Pakistan were determined. The nano-sized bentonite was used to prepare aluminum modified bentonite (AMB). The experiments included batch sorption experiments in which the influence of the adsorption condition, including pH, contact time, dosage of adsorbent and initial concentration of metal on the metal removal efficiency was investigated. Under Optimal conditions, the adsorbent exhibited excellent removal efficiencies for Cr, Ni and Pb, achieving 99.85 %, 99.95% and 99.63% respectively. The experimental equilibrium data showed a better agreement with the Freundlich isotherm model, suggesting that the adsorption process occurred on a heterogeneous surface through multilayer adsorption, while the D–R and Temkin model confirmed that adsorption process was mainly physical. FTIR, XRD, SEM and EDX were used to identify and analyze the changes in structure and surface that are responsible for the increased metal binding. The outcomes suggest that the use of aluminum treated bentonite is cost-effective and it is natural and can be applied as remedial agent to clean heavy metal contaminated water, so it is a promising solution in developing countries to make their wastewater management facilities viable in green buildings.

Keywords: Bentonite clay; Heavy metal adsorption; Aluminum modified bentonite (AMB); Wastewater treatment; Lead chromium and nickel removal; Adsorption isotherms; Garhi Chandan

Lethality-Driven Hazard Ranking for Underground Coal Mining Fatalities in Pakistan: A CRITIC–MARCOS Analysis of Technical Failure Pathways

Atif Javed[1], Rana Muhammad Asad Khan[2]*, Ghufran Ur Rehman[3], Dr. Hira Hameed[4]
[1]Central South University of China, China
[2 3]Pak-Austria Fachhochschule Institute of Applied Sciences and Technology, Haripur, Pakistan
[4] Department of Physics, University of Punjab
*Email:masadkhan87@gmail.com

Underground coal mining in Pakistan continues to face recurrent fatal accidents caused by methane explosions, toxic-gas exposure, roof and ground failures, flooding, blasting, mechanical haulage, and electrical hazards. Although earlier studies have reported accident patterns in Pakistan's coal sector, limited work has converted recent fatal-incident evidence into an objective and reproducible hazard-prioritization framework. This study develops a data-driven engineering assessment of fatal hazard pathways in Pakistan's underground coal mines using a newly compiled public-source dataset covering the period 2016–2026, supplemented by a historical listing of incidents from 2011–2015 for contextual background. After excluding security-related attacks that do not represent underground technical hazard mechanisms, 30 fatal technical incidents involving 164 fatalities from the 2016–2026 period were retained for the primary analysis. A decision matrix was constructed using three quantitative criteria: accident share, fatality share, and lethality factor. The Criteria Importance Through Inter criteria Correlation (CRITIC) method derived objective

criterion weights from the variability and conflict structure of the data, while the Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) method ranked hazard pathways according to their relative criticality. CRITIC results assigned the highest weight to lethality factor, followed by accident share and fatality share, indicating the importance of considering both occurrence and fatality intensity. The MARCOS ranking identified methane/gas explosion as the highest-priority fatal hazard pathway, followed by flooding/water inrush, suffocation/toxic-gas exposure, and collapse/ground failure. Flooding showed high lethality but was represented by fewer documented events; therefore, its ranking should be interpreted cautiously. These findings highlight methane control, ventilation reliability, gas monitoring, emergency preparedness, and ground-control management as urgent engineering priorities for reducing fatality risk in Pakistan's underground coal mines.

Keywords: Underground Coal Mining, Fatal Accidents, Mine-Safety, MARCOS multi-Criteria, Decision-making

Tectonic Controls on Large Bedrock Landslides in the Hunza Valley: An Interpretable Machine Learning and SHAP-Based Assessment

M. Farooq Ahmed[1]*, Iqra Hassan[2], Adnan Siddique[3], Ehtasham Naseer[4], Othmar Frey[5]

[1]M Farooq Ahmed, Department of Geological Engineering, University of Engineering and Technology Lahore, Pakistan

[2]Iqra Hassan, Department of Geological Engineering, University of Engineering and Technology Lahore

[3]Adnan Siddique, Remote Sensing and Spatial Analytics Lab. Information Technology University (ITU), Lahore, Pakistan

[4]Ehtasham Naseer, Remote Sensing and Spatial Analytics Lab. Information Technology, University Lahore, Pakistan

[5]Othmar Frey, Chair of Earth Observation and Remote Sensing, ETH Zurich, Zurich, Switzerland, Switzerland

**Email: mfageo@uet.edu.pk*

Understanding the relative roles of tectonic and climatic controls on large bedrock landslides remains a key challenge in active orogenic belts. In this study, remote sensing, field observations, and interpretable machine learning tools are integrated to investigate the factors governing large, deep-seated landslides in the Hunza region. A field-validated landslide inventory, derived from anomalous topographic and geomorphic signatures, was used as a training mask. An ALOS PALSAR DEM and multi-source geospatial data including; GNSS-derived crustal velocities, slope, aspect, curvature, elevation, drainage proximity, fault proximity, seismic hazard, rainfall, topographic wetness index, and vegetation cover.

This study quantitatively assesses the relative contributions of multiple conditioning and triggering factors controlling large bedrock landslides using interpretable machine learning models. Three models (Random Forest, XGBoost, and MLP neural network) were trained and interpreted using SHapley Additive exPlanations (SHAP) to quantify feature contributions. All models achieved high predictive performance (AUC up to 0.98). SHAP-based interpretation reveals that tectonic parameters, particularly crustal velocity and proximity to active thrust faults, consistently rank as the best predictors of landslide occurrence, whereas rainfall likely acts as a secondary or transient trigger. Furthermore, spatial clustering of deep-seated landslides (e.g., Mayoon, Miacher, and Budalas) within zones of elevated deformation (~25 mm/yr) within the active collision zone is consistent with progressive rock mass weakening and long-term slope destabilization.

These results highlight the importance of tectonic forcing in preconditioning large bedrock landslides, with climatic inputs facilitating episodic reactivation. The integration of geodetic data with interpretable machine learning provides a quantitative framework for improving landslide hazard assessment in such tectonically active mountainous regime.

Keywords: Bedrock landslides; Tectonic velocity; SHAP; XG Boost; MLP Neural Network.

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