Unlocking Trapped Data – Case Study for the SUTGMM Programme

شماره کتابشناسی ملی	:	۱۰۴۹۸۸۲۰
عنوان و نام پدیدآور	:	Unlocking trapped data: case study for the SUTGMM Programme, authors Hamid Nazar [et al.].; Research Institute for Earth Sciences.; with cooperation UNESCO Chair on Coastal Geo-Hazard Analysis.
شابک	:	۹۷۸-٦۲۲-۱٥۸۲-۰٦-۸
وضعیت اجرای طرح	:	تهران: نشر خزه، ۱۴۰۵.
مشخصات ظاهری	:	g، ۱۳۷ ص.: مصور، جدول، نقشه (بخشی‌رنگی)، نمودار (رنگی).
یادداشت	:	زبان: انگلیسی. کد طرح ۲۱۳-ط-پ-۰۴.
یادداشت	:	Nazari Hamid, Abassi Ramin, Arefipour Saeed, Karami Jalal.
یادداشت	:	کتابنامه: ص. ۱۰٤-۱۱٤.
توصیفگر	:	برنامه نقشه‌برداری زمین‌شناسی موضوعی یکپارچه مبتنی بر سرور Server-Based Unified Thematic Geological Mappingلاتین
توصیفگر	:	نقشه‌برداری Surveying زمین‌شناسی Geology داده‌های آماری Statistical Data مدیریت داده‌ها Data Management
توصیفگر	:	مکران Mokran (Iran)
دسترسی و محل الکترونیکی	:	c٤٥fc١٨٠-baeb١f٨٨d-٤٢٤-٧٢e٦e-٣c٢١a٦d

Unlocking Trapped Data – Case Study for the SUTGMM Programme

Authors:

Hamid Nazari

Ramin Abbasi, Saeed Arefipour, Jalal Karami

نشرخزه

اطلاعات گزارش

عنوان: رمز گشایی داده های به دام افتاده: مطالعه موردی برای برنامه_SUTGMM
مجری: پژوهشکده علوم زمین
زبان مرجع: انگلیسی
خروجی: تحلیل و مقاله
نویسندگان: حمید نظری، رامین عباسی، سعید عارفی‌پور، جلال کرمی
رئیس کرسی یونسکو در مخاطرات زمین شناختی ساحلی: حمید نظری
مسئول شورای اجرایی: مرتضی طالبیان
ناشر: نشر خزه
با همکاری کرسی یونسکو در مخاطرات زمین شناختی ساحلی
چاپ اول: ۱۴۰۴
شمارگان: ۵۰ نسخه
صفحات: ۱۳۷
شابک: ۸-۰۶-۱۵۸۲-۶۲۲-۹۷۸
khazepub@gmail.com

Report Information

Title: Unlocking Trapped Data – Case Study for the SUTGMM Programme

Employer: Research Institute for Earth Sciences

Original language: English

Output: Report, Scientific paper

Authors: Hamid Nazari, Ramin Abbasi, Saeed Arefipour, Jalal Karami

Chairholder in the UNESCO Chair on Coastal Geo-Hazard Analysis: Hamid Nazari

Head of the Executive Council: Morteza Talebian

Publisher: Khazeh Publication

with cooperation UNESCO Chair on Coastal Geo-Hazard Analysis

First Edition: 2026

Edition number: 50

Page: 137

Shabak: 978-622-1582-06-8

khazepub@gmail.com

Scientific Council

Name	Affiliation
Iraj Abdollahie Fard	Exploration Directorate of NIOC
Behrouz Abtahi	Shahid Beheshti University (SBU)
Philippe Agard	University of Sorbonne
Hamid Alizadeh Lahijani	Iranian National Institute for Oceanography and Atmospheric Science
Ryo Anma	Tokushima University
Constantin D. Athanassas	School of Mining and Metallurgical Engineering, National Technical University of Athens (NTUA), Greece
Franck A. Audemard	Department of Geology, Central University of Venezuela
Alice Aurelie	UNESCO Water Sciences Division
Ara Avagyan	IGS: Institute Geological Sciences
Yeong Bae Seong	Korea University
Rick J Bailey	IOC-UNESCO Indian Ocean Tsunami Warning and Mitigation System/ UNESCO
Abbas Banj Shafiei	Urmia University
Eric Barrier	University of Sorbonne
Jean Chery	University of Montpellier

Yahya Djamour	Shahid Beheshti University (SBU)
Dariush Esmaili	University of Tehran
Issa El-Hussain	Sultan Qaboos University
Aram Fathian Baneh	University of Calgary
Hassan Fazeli Nashli	University of Tehran
Magdi Guirguis	Institut français d'archéologie orientale du Caire
Ekkehard Holzbecher	German University of Technology in Oman
Egor Krasinskiy	Underwater research center Russian Geographical Society
Razyeh Lak	Research Institute for Earth Sciences
John Lambert	Deltares, UNESCO
Mohammad Mokhtari	International Institute of Earthquake Engineering and Seismology
Hamid Nazari	Research Institute for Earth Sciences
Jafar Omrani	CGMW- Geological Survey of Iran
Klaus Reicherter	Aachen University
Jean-François Ritz	University of Montpellier
Stefano Salvi	National Institute of Geophysics and Volcanology (INGV)
Morteza Talebian	Research Institute for Earth Sciences
Mohammad Tatar	International Institute of Earthquake

	Engineering and Seismology
Katerina Theodorakopoulou	Hellenic Open University-School of Applied Arts and Sustainable Design, Greece
Judith Thomalsky	German Archaeological Institute Tehran Branch
Richard Walker	University of Oxford
Wenjiao Xiao	Chinese Academy of Sciences
Alireza Zarasvandi	Iranian Research Organization for Science & Technology (IROST) – Ministry of Science, Research & Technology
Mahdi Zare	International Institute of Earthquake Engineering and Seismology

Executive Council-Abroad

Name	**Affiliation**
Nasir Ahmadi	Environmental Protection Organization of Mazandaran Province
Arash Amini	Golestan University
Mir Ali Asghar Mokhtari	University of Zanjan
Alireza Amrikazemi	Scientific Coordinator, Qeshm Island UNESCO Global Geopark
Somayeh Arab	University of Tehran

Parviz Armani	Imam Khomeini International University
Asghar Dolati	Kharazmi University
Fahimeh Foroghi	Iranian National Institute for Oceanography and Atmospheric Science
Abdolazaim Ghanghormeh	Golestan University
Habibolah Ghasemi	Shahrood University of Technology
Ataollah Kavian	Environmental Protection Organization of Mazandaran Province
Hossein Kouhestani	University of Zanjan
Mahdi Moghimi	University of Zanjan
Ali Akbar Momeni	Shahrood University of Technology
Babak Moradi	Iranian National Institute for Oceanography and Atmospheric Science
Seyed Mohsen Mortazavi	Hormozgan University
Hasan Nasrollah Zadeh	Caspian Sea Ecological Research Center
Ehsan Pegah	Kharazmi University
Abdolwahed Pehpouri	Qeshm Island UNESCO Global Geopark
Ahmadreza Rabani	University of Science and Technology

	of Mazandaran
Mahdi Rahmanian	Shargh Daily newspaper
Masoud Sadri Nasab	University of Tehran
Mojtaba Safari	University of Mazandaran
Mohammad Tatar	International Institute of Earthquake Engineering and Seismology
Mojtaba Yamani	University of Tehran

Executive Council-RIES and GSI (Board of Directors)

Name	**Affiliation**
Seyed Mahmoud Fatemi	Deputy Minister and General Director
Morteza Talebian	Director in RIES and President of the Executive Board
Mahdi Badpa	Vice President
Mahmoudreza Majidifard	Deputy in Research
Majid Pourkerman	AI-GEOARCH Specialist
Mehdi Basavand	Head of Youth Section
Zaynab Kazeminia	Head of the Secretariat

Executive members (RIES):

Hourieh Alibeygi	Secretary
Keivan Ajdari	Educational expert
Afshin Akbarpour	Academic Advisor
Mohammad Reza Ghasemi	Academic Advisor
Elaheh Ghayoumi	Web Designer

Hamoon Memarian	IT and Information
Manouchehr Qorashi	Advisor
Shirin Safavi	Communication Affair
Majid Taherverdi	Financial Affair
Alireza Vaezi	Academic Advisor

Executive members (GSI):

Saeed Arefipour	Research Expert
Hanieh Bakhshaei	International Affair
Reza Behbahani	Research Expert
Javad Darvishi khatooni	Research Expert
Mohammadreza Ensani	Research Expert
Marziyeh Estrabi	CGMW
Narges Ghamami	Executive Director of the Geosciences Quarterly
Gholamreza Hoseinyar	Research Expert
Somayeh Habibi	Research Expert
Mojtaba Kavianpour	Research Expert
Maryam Miraftab	Public Relation Affair
Elham Moeini	Public Relation Affair
Mohammad Ali Shokri	Research Expert
Faramarz Taheri Dadgar	Public Relation Affair

Contents

Abstract 1

Chapter 1: Introduction (Problem Statement, Rationale and Digital Resources) 3

1.1 Introduction 4

1. 1. Historical and Geographical Context 4

1.1.2 Study Area and Area of Interest (AOI) 6

1.1.3 Geological and Tectonic Setting 12

1.1.4 Tectonic Setting of Makran 14

1.2 Problem Statement 19

1.3 Rationale, Background, and Alignment with Project Scope 19

1.3.1 Rationale for the Project 19

1.3.2 Background 20

1.3.3 Alignment with Project Scope 22

1.4 Contribution to the Bibliography and Digital Resources 29

1.5 Scope and Data Collection 30

1.5.1 Out of Scope 36

1.6 Workflow and Protocol for Server-Based Unified Thematic Geological Mapping (SUTGMM) 39

1.6.1 Data Ingestion and Preprocessing 41

1.6.2 Feature Extraction and Harmonization 42

1.6.3 Training Data Preparation and Supervised Classification 43
1.6.4 Iterative Field Validation and Model Refinement 44
1.6.5 Integration within the Unified Geospatial Framework 44
1.6.6 Reproducibility, Transparency, and Scalability 45
1.7 Objectives 48
1.7.1 Primary Objective 48
1.7.2 Secondary (Specific) Objectives 50
Chapter 2: Theoretical Foundations and Literature Review . 52
2.1 The Concept of Trapped Data 53
2.1.1 Establishment of Domain-Specific Data Curation and Governance Practices 53
2.1.2 Development of Scalable and Reproducible Data Integration Pipelines 54
2.1.3 Validation through Pilot Use Cases in the Makran Zone 55
2.2 Data Governance in Geosciences 56
2.2.1 Governmental Agencies 57
2.2.2 Academic Institutions 58
2.2.3 Industry Stakeholders 58
2.3 Server-Based GIS Architectures 59
2.3.1 Remote Sensing and Publicly Available Data 59
2.3.2 Data Stewardship and Accessibility Protocols 60
2.4 Metadata Standards and Interoperability 61

2.4.1 Definition of Ethical, Privacy, and Data Governance Guidelines 61

2.4.2 Data Sources and Accessibility 62

Chapter 3: Unlocking Trapped Data 65

3.1 Introduction UTD 66

3.2 Georeferencing and Spatial Integration 67

3.3 Thematic and Cartographic Classification 68

3.4 Multi-Scale Mapping for Regional and Local Analyses . 68

3.5 Unlocking Scientific Value through Integration 69

3.6 Unlocking Trapped Data (continued: Integration with Remote Sensing and Analytical Workflows) 71

3.6.1 Integration with Remote Sensing Data 71

3.6.2 Machine-Learning Classification and Thematic Synthesis 72

3.6.3 Integration of Structural and Geophysical Data 73

3.7 Metadata, Provenance, and Reproducibility 74

3.8 Outcome: Dynamic, Multi-Source Geological Knowledge 74

3.9 Data Processing and Integration Workflows 75

3.9.1 Data Ingestion and Preprocessing 75

3.10 Metadata Enrichment and Data Cataloging 76

3.11 Data Harmonization and Normalization 77

Chapter 4: Integrated Analytical SUTGMM Framework and Outputs for Unlocking Trapped Data 78

4.1 Feature Extraction and Analytical Preparation 79

4.2 Data Integration and Unified Framework Construction 79
4.3 Iterative Validation and Quality Control 80
4.4 Preparation for Analytical Outputs 81
4.4.1 Outcome: Integrated, Actionable Geoscience Data 81
4.4.2 Analytical Outputs and Geovisualization Products 82
4.5 Unified Thematic Geological Maps 82
4.6 Three-Dimensional Conceptual and Subsurface Models 83
4.7 Mineral Potential and Geochemical Screening Layers .. 83
4.8 Interactive Geovisualization Dashboards 84
4.9 Metadata and Provenance Documentation 85
4.10 Deliverable Summary 85
Chapter 5: Conclusions, Project Boundaries, Risk Governance, and Strategic Impact 87
5.1 Project Limitations, Exclusions, and Risk Management. 88
5.1.1 Project Limitations 88
5.2 Exclusions 89
5.3 Risk Management Strategies 90
5.4 Implications for Project Deliverables 91
5.5 Expected Outcomes and Impact 92
5.5.1 Scientific Outcomes 92
5.5.2 Institutional and Capacity-Building Outcomes 93
5.5.3 Socio-Economic and Practical Impacts 94
5.5.4 Long-Term and Transferable Benefits 94
5.6 Summary 95

5.7 Project Timeline and Implementation Plan 96
5.7.1 Phase 1: Project Initiation and Data Inventory (Month 1–2) 96
5.7.2 Phase 2: Data Preprocessing and Georeferencing (Month 2–4) 97
5.7.3 Phase 3: Data Harmonization and Feature Extraction (Month 4–6) 98
5.7.4 Phase 4: Data Integration and Unified Framework Construction (Month 6–8).. 98
5.7.5 Phase 5: Thematic Mapping, Machine-Learning Classification, and Analytical Outputs (Month 8–10) 99
5.7.6 Phase 6: Geovisualization and Decision-Support Tools (Month 10–11) 100
5.7.7 Phase 7: Reporting, Training, and Knowledge Transfer (Month 11–12) 101
5.8 Conclusion 103
References 106

Table of Figures

Figure 1. The Area of Interest (AOI) for the SUTGMM highlighted with a green polygon. Dark shaded rectangles indicate the four 1:100,000 geological sheets of Kahir, Pir Sohrab, Konarak and Chabahar.**Error! Bookmark not defined.**
Figure 2. Study area encompassing the area of interest (AOI) and the additional buffer zone.**Error! Bookmark not defined.**

Figure 3. Tectonic setting of the Makran region, showing tectonostratigraphic zones and major structures, including the accretionary wedges and pull-apart basins (Haghipour and Burg, 2014; Burg, 2018). ....**Error! Bookmark not defined.**
Figure 4. Seismotectonic configuration of Makran and surrounding areas. The subduction front in the Oman Sea marks the convergence between the Arabian and Eurasian plates. Fault traces are compiled and modified after Fathian (2022). Red shaded polygon mark the AOI. Grey, red, and blue beachballs represent fault plane solutions from the the Global Centroid Moment Tensor (GCMT; https://www.globalcmt.org), body waveform, and the first motions catalogs (see Fathian, 2022 and the references therein). Red arrows represent GPS velocity vectors relative to a stable Eurasian plate (Khorrami et al., 2019). Background is the shaded relief from SRTM 90m (Farr et al., 2007) and GEBCO Global Bathymetry 15 arc-sec (GEBCO Compilation Group, 2023) visualizing surface topography and bathymetry. ....**Error! Bookmark not defined.**
Figure 5: Integrated and homogeneous geological map, example implemented using artificial intelligence in the Makran area, scale 1:100000 23
Figure 6: Pilot Project 1 involved the development of a server-based integrated geospatial framework for the Lut Project, encompassing the extent of eleven 1:100,000-scale map sheets (see above). In addition, a detailed geological map of the Lut Desert was compiled at a scale of 1:100,000. 25
Figure 7: Pilot Project 2 comprised the preparation of a server-based integrated geospatial map for the Makran Project, covering an area equivalent to approximately 2.5 sheets at a scale of 1:100,000 (upper section). In addition, structural cross-sections were constructed and restored using Move software (middle section). The project further included

the compilation of the Zirdan geological sheet at a scale of 1:50,000 (lower section). 27
Figure 8: Pilot Project 3 involves the preparation of the Preliminary Geomap (v4), a server-based integrated geological map at a scale of 1:50,000, currently under development. This dataset covers the broader Nain Block megaproject area and integrates geological information from five 1:100,000-scale map sheets as well as twenty 1:50,000-scale geological sheets. 28
Figure 9. Workflow and protocol for Server-based Unified Thematic Geological Mapping of Makran (SUTGMM) using multi-source remote sensing data and machine learning. The process includes feature extraction from Sentinel-1, Sentinel-2, Landsat 8, ASTER, and SRTM DEM data, supervised classification, field-checking, and iterative refinement. The final outputs include a unified geological map, structural section, and integrated geodatabase 47
Figure 10: Ravar Terrain Aspect Map: Aspect map generated from the 10 m DEM of the Ravar study area. This morphometric layer captures slope direction patterns and provides supporting terrain characterization for geomorphological interpretation. 63
Figure 11: Full-Model K Prediction Map generated through integrated machine-learning analysis of harmonized terrain, radar, NDVI, and anthropogenic features, demonstrating the operationalization of previously trapped multi-source geospatial data within the SUTGMM 70

Table of Table

Table 1: List of the maps used in the project. 30
Table 2: Summary Timeline Table 102

Abstract

Large volumes of geoscientific data related to the Makran Zone have been generated by governmental agencies, academic institutions, and industry actors over several decades. Despite their high potential scientific and economic value, a significant portion of these datasets remains fragmented, underutilized, or effectively inaccessible due to institutional silos, heterogeneous data formats, incomplete metadata, and the absence of coherent data governance frameworks. This phenomenon, commonly referred to as "trapped data," limits integrated geological interpretation, evidence-based decision-making, and value creation from existing data assets.

This research proposes an end-to-end, server-based framework for unlocking trapped geological data within the SUTGMM (Server-Based Unified Thematic Geological Mapping) Programme. Using the Makran Zone as a case study, the primary objective is to demonstrate how existing and underexploited geoscience datasets can be systematically identified, curated, integrated, and transformed into high-value geological products within a one-year timeframe, without relying on new data acquisition campaigns.

The proposed approach combines data governance, technical infrastructure, and applied geospatial analytics. The methodology includes (i) a comprehensive inventory of Makran-related geoscience assets and the establishment of data stewardship, access, and usage policies; (ii) the development of a domain-specific metadata and discovery layer to surface hidden or poorly documented datasets; (iii) the implementation of modular data integration pipelines for harmonizing heterogeneous geospatial data while preserving provenance and traceability; and (iv) the generation of value-added analytical outputs through reusable geospatial analytics and visualization tools. Two pilot use cases—integrated tectonic and structural mapping, and mineral potential and soil/geochemical screening—are used to validate the framework and demonstrate tangible scientific and managerial value.

Expected outcomes include curated and discoverable geoscience datasets, reproducible analytical workflows, interactive maps and dashboards for stakeholders, and a set of best-practice guidelines addressing ethics, privacy, and governance of sensitive geospatial data. By embedding these outputs within the SUTGMM ICT and knowledge-based infrastructure, the project ensures scalability and long-term reuse.

Overall, this study demonstrates how unlocking trapped data can accelerate scientific production, enhance data-driven geological mapping, and create added value for policy, research, and industry. The Makran case study provides a transferable model for similar geoscience initiatives facing data fragmentation and governance challenges within the SUTGMM programme and beyond.

Keywords: Unlocking Trapped Data; Confined data, geological data integration, geological mapping, SUTGMM programme, Makran region

Chapter 1: Introduction (Problem Statement, Rationale and Digital Resources)

1.1 Introduction

1. 1. Historical and Geographical Context

The Makran region, extending across southeastern Iran and southwestern Pakistan along the northern margin of the Oman Sea, represents a geologically complex and strategically significant domain situated between the Strait of Hormuz and Karachi. Characterized by east–west–trending mountain belts and rugged topography, it occupies a critical position at the intersection of tectonic, maritime, and socio-economic systems. Historically known as “Maka” during the Achaemenid period, the region has held administrative and strategic importance for over three millennia and continues to gain relevance due to expanding coastal development and infrastructure growth.

Geodynamically, Makran constitutes an active subduction system where the Arabian Plate descends beneath the Eurasian Plate, forming one of the few extensively exposed accretionary wedges worldwide. This setting provides a natural laboratory for investigating subduction dynamics, sediment accretion, forearc basin evolution, crustal deformation, and associated seismic and tsunami hazards. The region encompasses a broad lithostratigraphic spectrum, including Mesozoic ophiolitic complexes, deep-marine sedimentary assemblages, thick Cenozoic turbidites, and Quaternary coastal and alluvial deposits. These units directly influence mineral potential, hydrocarbon prospectivity, groundwater systems, geohazard susceptibility, and engineering geological conditions, necessitating integrated, multi-disciplinary analysis.

Over several decades, extensive geological, geophysical, geochemical, marine, and remote sensing investigations have produced large and diverse datasets, including geological maps, structural cross-sections, stratigraphic logs, seismic profiles, gravity and magnetic surveys, geochemical assays, satellite-derived deformation measurements, and bathymetric data. However, these datasets remain highly fragmented across institutions, stored in heterogeneous formats, and frequently lack standardized metadata, consistent coordinate systems, and harmonized stratigraphic nomenclature. Legacy analog archives, incomplete documentation, and weak governance mechanisms further constrain interoperability and reproducibility. Consequently, substantial informational value remains effectively "trapped," limiting cross-disciplinary synthesis, integrated hazard assessment, and data-driven decision-making while increasing redundancy in field investigations.

In response, the Server-Based Unified Thematic Geological Mapping (SUTGMM) Programme is proposed as a conceptual and operational framework designed to transform dispersed geoscientific information into an integrated, interoperable, and analytically accessible digital infrastructure. The programme advances a transition from static, isolated cartographic products toward dynamic, server-based environments where thematic layers are harmonized, metadata standards are enforced, provenance is preserved, and analytical workflows are reproducible. By embedding data governance principles within a centralized geospatial architecture, SUTGMM seeks to unlock latent informational value embedded in both historical and contemporary datasets.

The Makran Zone serves as an appropriate pilot case study due to its tectonic complexity, abundance yet heterogeneity of datasets, transboundary character, and increasing socio-economic importance. Framed within this broader epistemic shift toward data-centric geoscience, the study positions Makran not only as a subject of geological investigation but as a model for advancing unified thematic mapping, structured data governance, and digital geoscience infrastructure development.

1.1.2 Study Area and Area of Interest (AOI)

The delineation of the Area of Interest (AOI) based on the four 1:100,000 geological sheets of Chabahar, Pir Soharab, Konarak, and Kahir reflects a deliberate cartographic and analytical strategy aimed at ensuring spatial coherence and geological continuity across sheet boundaries. These sheets collectively encompass a structurally complex segment of the Makran Zone, characterized by lithological heterogeneity, active tectonics, coastal–marine interactions, and significant geomorphological variability. The integration of these adjacent quadrangles into a single analytical framework enables the preparation of a harmonized geological map that transcends administrative and cartographic segmentation (Figure 1).

The selection of the 1:100,000 scale as the primary cartographic reference is methodologically appropriate for regional-scale synthesis combined with sufficient detail for structural and lithological discrimination. At this scale, major stratigraphic units, fault systems, fold axes, mélanges, accretionary complexes, and sedimentary facies variations can be consistently represented while preserving compatibility with national geological mapping standards. Moreover, this scale provides an optimal balance between resolution and computational efficiency for remote sensing–based thematic classification within the SUTGMM framework.

The inclusion of a buffer zone ranging from approximately 13 to 28 km beyond the formal boundaries of the four sheets constitutes a critical methodological enhancement rather than a simple spatial extension. Geological systems, particularly in tectonically active regions such as the Makran accretionary prism, rarely conform to artificial sheet boundaries. Structural trends, lithological transitions, sediment dispersal systems, and tectonostratigraphic domains commonly extend across multiple map sheets. Without the incorporation of peripheral data, interpretations risk edge effects, truncation of structural features, and misrepresentation of regional continuity.

The buffer serves two primary scientific and cartographic functions (Figure 2):

Enhanced Structural and *Lithological* Interpretation

The Makran Zone is dominated by large-scale compressional structures, thrust systems, imbricate fan geometries, and oblique fault networks associated with subduction processes. These structural features often exhibit wavelengths and orientations that extend well beyond individual quadrangle limits. By incorporating the buffer zone, it becomes possible to:

- Trace fault continuities and verify displacement patterns across sheet margins;
- Evaluate fold geometry and vergence trends within a broader tectonic context;

- Assess lateral facies changes and depositional environments beyond the confined AOI;
- Reduce boundary-induced bias in automated lineament extraction and machine-learning classification.
- From a remote sensing perspective, feature extraction algorithms—particularly those relying on texture, slope, and structural orientation—benefit significantly from extended spatial windows. The buffer reduces edge artifacts in raster-based processing and enhances the reliability of derived indices such as lineament density, curvature, and terrain ruggedness.

Integrated and Harmonized Geological Mapping

Each of the four geological sheets was originally produced as an independent mapping product, potentially incorporating variations in lithological nomenclature, symbology, stratigraphic subdivision, and structural interpretation. The preparation of a unified geological map requires systematic harmonization of these elements. The buffer zone supports this process by:

Allowing reconciliation of lithological unit boundaries where inconsistencies occur across adjacent sheets;

- Enabling normalization of stratigraphic hierarchies and unit codes within a consistent schema;
- Providing spatial context to resolve discrepancies in fault placement or contact interpretation;
- Facilitating seamless vector integration and topological correction across sheet boundaries.

In the SUTGMM workflow, the buffer also enhances machine-learning training and validation. Classification models trained on lithological polygons benefit from increased sample diversity when edge-adjacent units are included. Additionally, cross-validation procedures become more robust when classification performance can be assessed beyond strict sheet limits.

From a geomorphological perspective, the extended AOI captures coastal–marine interactions, alluvial systems, and erosional surfaces that influence sedimentary processes within the mapped sheets. In coastal Makran, for example, marine terraces, tidal flats, and deltaic systems may straddle sheet boundaries. Incorporating these transitional zones supports more coherent environmental and stratigraphic interpretation.

The buffer width (13–28 km) was determined to ensure coverage of major structural corridors and lithological transitions while maintaining manageable computational and analytical scope. Variability in buffer extent reflects the geometric configuration of the sheets and the orientation of dominant tectonic trends. Where structural continuity was particularly critical, the buffer was extended accordingly to preserve interpretive integrity.

Within the server-based SUTGMM infrastructure, the AOI and its buffer were implemented as hierarchical spatial layers. This configuration allows analyses to be performed either within the strict quadrangle boundaries or across the extended regional domain. Such flexibility supports both detailed quadrangle-level mapping and broader tectonic synthesis.

Ultimately, the integration of the four 1:100,000 sheets and the surrounding buffer zone enables the production of a unified geological map that is:

- Structurally coherent across sheet boundaries;
- Lithologically harmonized and terminologically standardized;
- Compatible with remote sensing–derived thematic layers;
- Free from cartographic discontinuities and edge artifacts;

Suitable for downstream applications such as mineral potential assessment, structural modeling, and hazard evaluation.

By embedding the AOI within a broader spatial context, the project ensures that geological interpretation is driven by natural system continuity rather than artificial cartographic constraints. This approach enhances analytical reliability, supports reproducible workflows, and strengthens the scientific validity of the resulting unified geological map for the Makran coastal region.

Figure 1. The Area of Interest (AOI) for the SUTGMM highlighted with a green polygon. Dark shaded rectangles indicate the four 1:100,000 geological sheets of Kahir, Pir Sohrab, Konarak and Chabahar

Figure 2. Study area encompassing the area of interest (AOI) and the additional buffer zone.

1.1.3 Geological and Tectonic Setting

The tectonic framework of the Makran region plays a pivotal role in elucidating the geodynamic development of the Middle East and the progressive closure of the Neo-Tethys Ocean. In this sector, the northward subduction of the Arabian Plate beneath Eurasia stands in marked contrast to the continent–continent collision observed in the Zagros Mountains to the west, underscoring the spatial variability and structural complexity of plate boundary processes (Burg, 2018). Evidence for sustained subduction is provided by both

Cretaceous and Quaternary volcanic arcs, which record prolonged magmatic activity associated with convergent margin dynamics. Remnants of older, now eroded or subducted arcs further constrain the tectonomagmatic evolution of the upper plate and document episodes of fragmentation and reorganization (Arthurton et al., 1982; Burg, 2018).

The identification of Jurassic rift-related magmatism followed by Cretaceous arc magmatism indicates that the Central Iran block experienced substantial pre-collisional extensional fragmentation. This early tectonic segmentation has important implications for reconstructing the architecture and evolution of the regional orogenic system (Burg, 2018). Moreover, correlations between the tectonic evolution of Makran and that of the Oman Mountains along the subducting Arabian Plate provide an integrated perspective on the broader geodynamic framework of the region (Burg, 2018).

Overall, the Makran domain represents a highly intricate and dynamically evolving tectonic environment (Figure 2-1), governed by the interaction of subduction, accretionary processes, seismic activity, surface uplift, and sedimentary accumulation. The relatively shallow geometry of Arabian Plate subduction beneath Eurasia has generated one of the largest accretionary prisms worldwide, characterized by voluminous sediment input, intense structural deformation, and heterogeneous seismic behavior. A comprehensive understanding of the Makran tectonic regime is therefore essential for evaluating seismic risk, refining regional geodynamic models, and clarifying the coupling between deep lithospheric processes and surface evolution. Continued integration of geological, geophysical, and geomorphological datasets is progressively improving constraints on the tectonic behavior of this active convergent margin.

1.1.4 Tectonic Setting of Makran

The Makran domain occupies southeastern Iran and southwestern Pakistan along the northern margin of the Gulf of Oman and constitutes a structurally intricate segment of the Arabia–Eurasia plate boundary. Its most prominent tectonic feature is a large accretionary complex generated by the ongoing northward subduction of the Arabian Plate beneath Eurasia (Figure 2 and Figure 3). This structure, commonly referred to as the Makran accretionary wedge, extends for nearly 1,000 km parallel to the trench and is laterally confined by major fault systems on both its eastern and western margins (Arthurton et al., 1982; McCall, 1985; Dolati, 2010; Haghipour and Burg, 2014; Gharibreza, 2016; Burg, 2018). Geodetic constraints and plate kinematic reconstructions demonstrate that active convergence between Arabia and Eurasia is ongoing, although the rate of shortening varies significantly along strike (Figure 3). Baseline measurements between Muscat (Oman) and Chabahar (Iran) yield a convergence velocity of approximately 19 mm/yr (Vernant et al., 2004; Khorrami et al., 2019). This motion reflects the broader northward displacement of the Arabian Plate, which descends beneath Eurasia along the Makran Trench.

Additional GPS data indicate that the present-day convergence rate between the Makran coastline (e.g., the Chabahar station) and stable Eurasia is on the order of 8 mm/yr (Vernant et al., 2004). Nevertheless, several studies report a pronounced eastward increase in convergence velocity, with estimates reaching 35.5–42 mm/yr in eastern Makran. This spatial gradient has been attributed to the anticlockwise rotation of the Arabian Plate relative to Eurasia (DeMets et al., 2010; Hatzfeld and Molnar, 2010; Burg, 2018).

Such along-strike variability in convergence rates has important implications for both the tectonic evolution and seismic behavior of the Makran subduction system. The progressive increase in shortening toward the east is consistent with the rotational kinematics of the Arabian Plate and is further supported by independent constraints derived from seafloor spreading rates and the azimuthal orientation of major plate-bounding faults (DeMets et al., 2010).

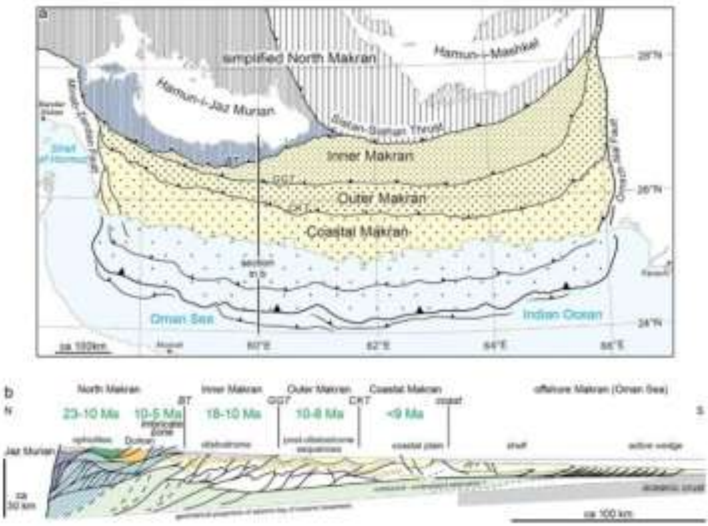


Figure 3. Tectonic setting of the Makran region, showing tectonostratigraphic zones and major structures, including the accretionary wedges and pull-apart basins (Haghipour and Burg, 2014; Burg, 2018).

The structural framework of the Makran accretionary wedge is fundamentally controlled by two major strike-slip fault systems that delineate its lateral boundaries (Figure 2 and Figure 3). Along the western margin, the dextral Minab–Zendan Fault System forms a critical tectonic interface. In particular, the Minab Fault demarcates the transition from oceanic subduction within the Makran domain to continent–continent collision in the Zagros orogenic belt (Stöcklin, 1968; Bird et al., 1975; Dolati, 2010; Haghipour and Burg, 2014). This right-lateral fault network accommodates relative plate motion between Arabia and Eurasia and serves as a structural boundary separating mechanically and kinematically distinct tectonic regimes (Paul et al., 2001; Molnar and Stock, 2009; Dolati, 2010; Haghipour and Burg, 2014; Burg, 2018).

The eastern limit of the Makran wedge is defined by the sinistral Chaman–Ornach–Nal Fault System, which extends offshore into the Owen Fracture Zone. These left-lateral structures partition deformation between the Makran–Arabian domain and the Indian subcontinent (Figure 4). The Indian Plate migrates northward relative to Eurasia at rates of approximately 40–50 mm/yr, substantially exceeding the convergence rate along the Makran subduction interface (Paul et al., 2001; Molnar and Stock, 2009; Dolati, 2010; Haghipour and Burg, 2014; Burg, 2018). This pronounced kinematic contrast emphasizes the importance of lateral faulting in accommodating differential plate motions along the broader Arabia–India–Eurasia plate boundary system.

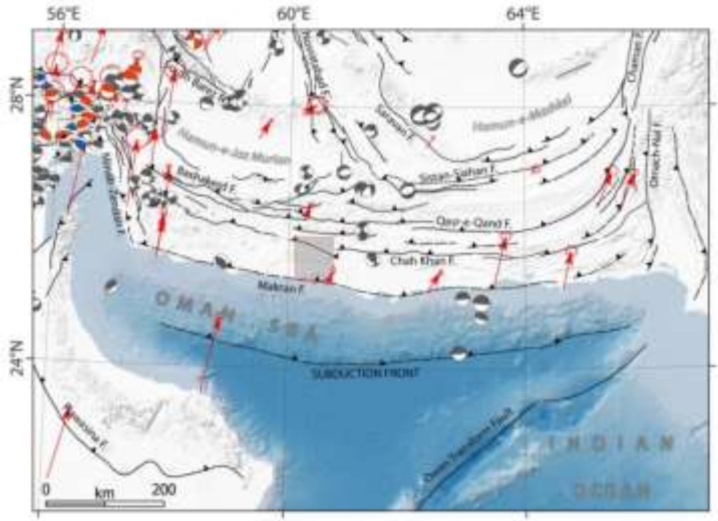


Figure 4. Seismotectonic configuration of Makran and surrounding areas. The subduction front in the Oman Sea marks the convergence between the Arabian and Eurasian plates. Fault traces are compiled and modified after Fathian (2022). Red shaded polygon marks the AOI. Grey, red, and blue beachballs represent fault plane solutions from the the Global Centroid Moment Tensor (GCMT; https://www.globalcmt.org), body waveform, and the first motions catalogs (see Fathian, 2022 and the references therein). Red arrows represent GPS velocity vectors relative to a stable Eurasian plate (Khorrami et al., 2019). Background is the shaded relief from SRTM 90m (Farr et al., 2007) and GEBCO Global Bathymetry 15 arc-sec (GEBCO Compilation Group, 2023) visualizing surface topography and bathymetry.

The internal architecture of the Makran domain is further diversified by the presence of multiple, subparallel accretionary wedges and associated pull-apart basins (e.g., Haghipour and Burg, 2014; Gharibreza, 2016). The Coastal Makran constitutes the emergent, onshore segment of the accretionary prism and is composed predominantly of intensely deformed Cenozoic terrigenous and fine-grained clastic sediments (Figure 4). Basinward, the Outer Makran represents the actively accreting frontal portion of the wedge, where ongoing sediment incorporation and structural deformation reflect continued subduction-related shortening.

Landward of this frontal domain, the Inner Makran and North Makran correspond to more internal and structurally complex segments of the accretionary system (Figure 3b). The Inner Makran is characterized by a thick succession of upper Eocene to lower Miocene turbiditic deposits that display an overall upward-thickening and coarsening stratigraphic trend, indicative of progressive sediment supply and basin infill during wedge evolution (e.g., Dolati, 2010; Haghipour and Burg, 2014). In contrast, the North Makran exposes tectonically imbricated assemblages of upper Cretaceous to Eocene igneous rocks, ophiolitic complexes, and associated deep-marine sedimentary units, recording earlier phases of oceanic crust formation and subsequent accretion (McCall, 1983; Haghipour and Burg, 2014).

Superimposed on this structural framework are major depressions such as Hamun-e-Jaz Murian and Hamun-e-Mashkel (Figure 4), which are interpreted as pull-apart structures functioning as forearc basins (Farhoudi and Karig, 1977; Dolati, 2010; Haghipour and Burg, 2014). The northern margin of the Makran is defined by the Quaternary sedimentary cover of the Jaz Murian depression in Iran and its counterpart, the Mashkel depression in Pakistan (Burg, 2018). Collectively, these tectonosedimentary elements contribute to the highly heterogeneous structural configuration of the Makran and exert significant control over sediment dispersal patterns, seismic activity, and ongoing surface deformation.

1.2 Problem Statement

The Multiple categories of geoscientific data—geological maps, geochemical datasets, geophysical surveys, remote sensing imagery, and exploration reports—exist for the Makran region. Nevertheless, several structural challenges limit their effective utilization:

- Institutional fragmentation of data repositories
- Heterogeneous data formats and coordinate systems
- Incomplete or absent metadata
- Lack of standardized access and governance policies

These limitations collectively result in the phenomenon of "trapped data," restricting integrated geological interpretation and evidence-based planning.

1.3 Rationale, Background, and Alignment with Project Scope

1.3.1 Rationale for the Project

Unlocking trapped data can:

- Reduce redundancy in new data acquisition
- Increase scientific efficiency and reproducibility
- Support strategic mineral exploration
- Enable data-driven policy and planning

Given the existing volume of underexploited datasets, a structured, governance-oriented solution is both timely and cost-effective.

1.3.2 Background

The systematic production, stewardship, and reuse of foundational geoscience data are central to sustainable development, mineral resource governance, geohazard mitigation, spatial planning, and long-term environmental management. Among geoscientific datasets, geological maps occupy a uniquely integrative role: they synthesize lithology, stratigraphy, structural architecture, and tectonic evolution into spatially explicit representations that function as both scientific records and decision-support instruments.

Despite decades of geological mapping, a substantial volume of high-value legacy data—particularly sheet-based geological maps and their explanatory materials—remains fragmented, inconsistently digitized, and poorly standardized. Many datasets persist in analog or semi-digital formats, lack structured metadata, employ heterogeneous attribute schemas and coordinate reference systems, and exhibit evolving stratigraphic nomenclature. As a result, although institutionally owned and scientifically valuable, these assets remain operationally constrained within modern geospatial ecosystems. This condition exemplifies "trapped data": information that is technically available yet functionally inaccessible for automated querying, cross-scale synthesis, reproducible analysis, and integration with complementary datasets such as geophysical grids, geochemical databases, remote sensing imagery, and digital elevation models.

The epistemic limitation stems from a structural gap between traditional cartographic production—designed for static dissemination—and contemporary paradigms of digital, server-based geoscience. Raster-only formats, non-standardized legends, absent machine-readable attributes, incomplete provenance documentation, and inconsistent spatial referencing collectively reduce interoperability, analytical transparency, and cost-efficiency. Consequently, new investigations may inadvertently replicate previously documented observations, diminishing cumulative knowledge gains.

Recent advances in geospatial technologies—including cloud-based infrastructures, interoperable web services, high-resolution Earth observation data, and modular data integration frameworks—provide a viable pathway for activating these legacy assets without initiating new field campaigns or constructing enterprise-scale platforms. Lightweight, standards-oriented approaches emphasize systematic data inventory, metadata enrichment, controlled vocabularies, coordinate normalization, provenance tracking, and reproducible processing pipelines. Rather than expanding data volume, they focus on enhancing discoverability, traceability, and semantic coherence.

Within this context, geological maps produced by authoritative institutions such as the Geological Survey of Iran represent strategically valuable core datasets. Available at multiple cartographic scales (e.g., 1:250,000 and 1:100,000), they support hierarchical analysis ranging from regional tectonic synthesis to localized lithological and structural assessment. When systematically digitized, vectorized, georeferenced to unified coordinate systems, and harmonized through standardized legend schemas, these maps can serve as foundational layers for integrated thematic mapping and multi-source geospatial workflows.

1.3.3 Alignment with Project Scope

The proposed project is therefore grounded in value activation rather than data expansion. Positioned at the intersection of geoscience knowledge management and digital transformation, it focuses on the structured inventory, normalization, and integration of existing geological assets within the Makran Zone under the SUTGMM (Server-Based Unified Thematic Geological Mapping) ICT and knowledge-based infrastructure. The initiative functions as a pilot-scale implementation, not a comprehensive national platform redesign, and does not pursue new data acquisition. Instead, it emphasizes cost-effective, incremental enhancement aligned with institutional capacity building and contemporary scientific standards.

Operationally, the project advances practical workflows for systematic data inventory; digitization and vectorization of legacy cartography; lithostratigraphic and structural standardization through controlled vocabularies; coordinate harmonization; structured metadata enrichment compliant with recognized geospatial standards; server-based geovisualization; and lightweight spatial analytics suited to exploratory research and regional planning. By embedding these processes within a centralized, server-based environment, the project transforms static archival products into functional, queryable, and interoperable thematic datasets.

Implemented in the tectonically complex and socio-economically significant Makran Zone, the initiative demonstrates a pragmatic model of digital transformation in the geosciences: incremental, standards-driven, and centered on unlocking latent value in legacy datasets. As such, it provides a replicable template for regions where extensive geological mapping exists but remains only partially integrated into contemporary digital geospatial infrastructures.

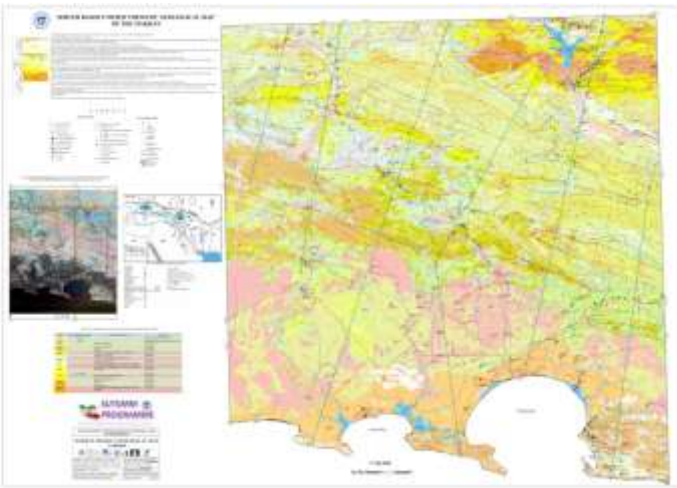
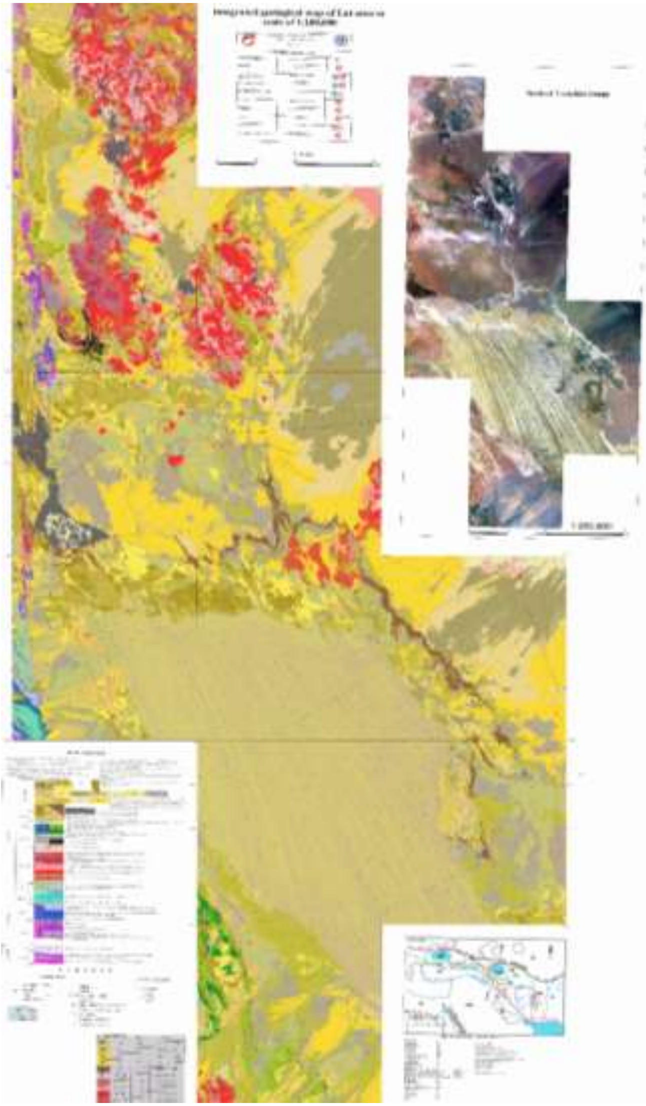


Figure 5. Integrated and homogeneous geological map, example implemented using artificial intelligence in the Makran area, scale 1:100000



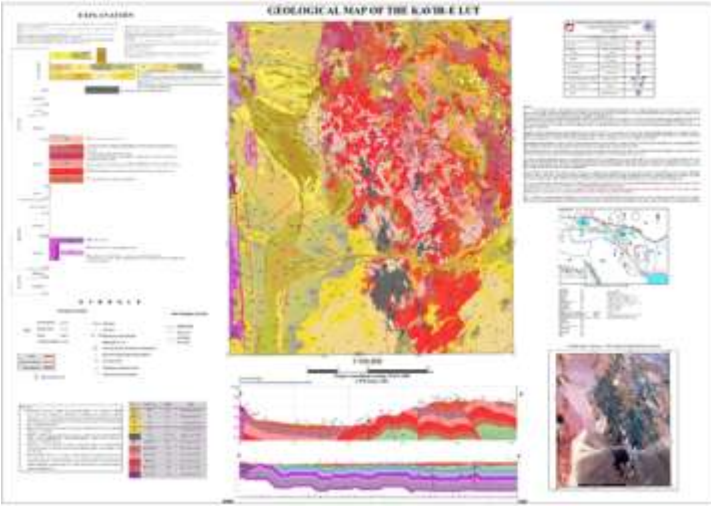
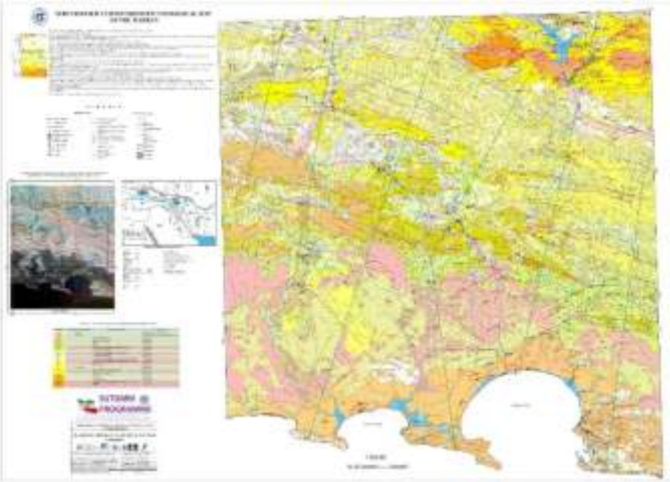
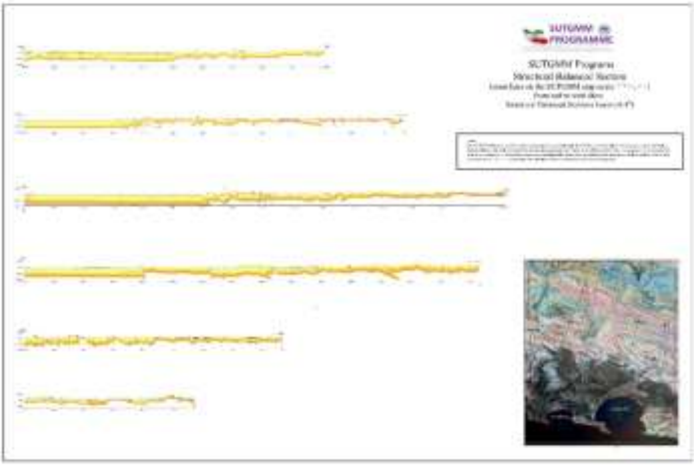


Figure 6. Pilot Project 1 involved the development of a server-based integrated geospatial framework for the Lut Project, encompassing the extent of eleven 1:100,000-scale map sheets (see above). In addition, a detailed geological map of the Lut Desert was compiled at a scale of 1:100,000.

This phase focused on standardizing spatial datasets, harmonizing stratigraphic and structural information across adjacent sheets, and establishing a unified digital platform to support regional geological analysis and future data integration.





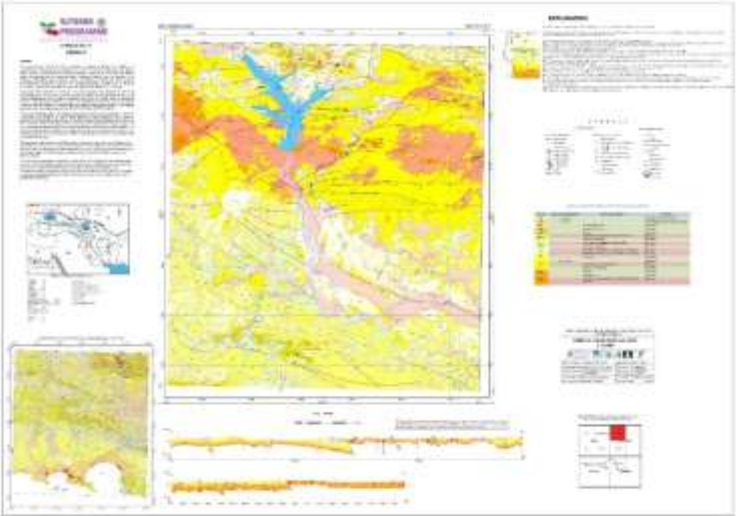


Figure 7. Pilot Project 2 comprised the preparation of a server-based integrated geospatial map for the Makran Project, covering an area equivalent to approximately 2.5 sheets at a scale of 1:100,000 (upper section). In addition, structural cross-sections were constructed and restored using Move software (middle section). The project further included the compilation of the Zirdan geological sheet at a scale of 1:50,000 (lower section).

This phase emphasized structural interpretation, kinematic analysis, and the integration of surface and subsurface datasets within a unified digital framework to enhance tectonic reconstruction and regional-scale geological modeling.

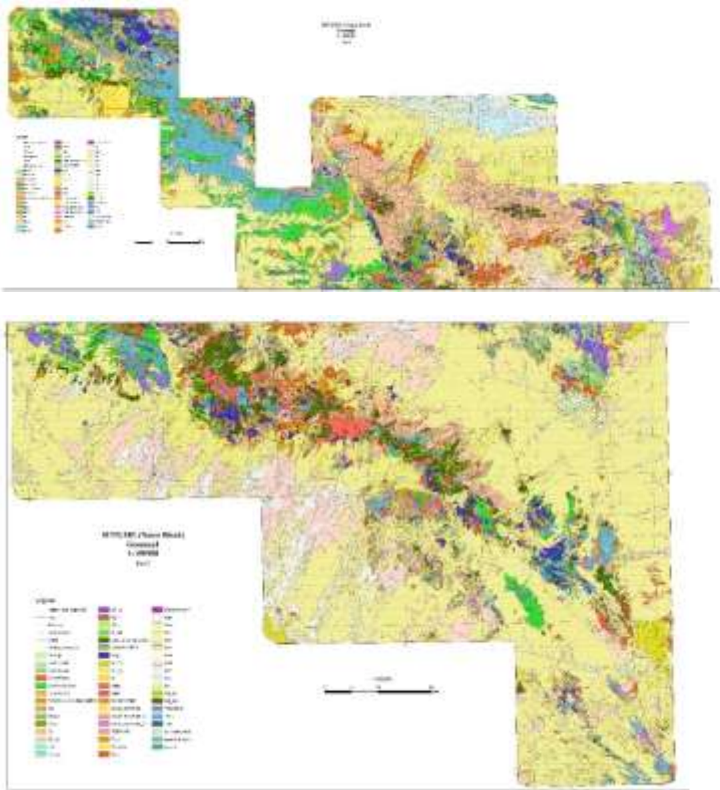


Figure 8. Pilot Project 3 involves the preparation of the Preliminary Geomap (v4), a server-based integrated geological map at a scale of 1:50,000, currently under development. This dataset covers the broader Nain Block megaproject area and integrates geological information from five 1:100,000-scale map sheets as well as twenty 1:50,000-scale geological sheets.

The objective of this phase is to establish a harmonized, high-resolution geodatabase that consolidates lithostratigraphic, structural, and geospatial datasets into a unified digital platform, thereby supporting regional-scale tectonic analysis and advanced geological modeling within the Nain Block.

1.4 Contribution to the Bibliography and Digital Resources

The digitized geological maps constitute a substantial contribution to the project's bibliographic and digital resource base, providing a reliable foundation for subsequent analyses, interpretations, and reporting. The systematic conversion of analog cartographic materials into standardized digital formats enables their effective use in modern geospatial analyses, including GIS-based modeling and integration with remote sensing datasets.

These digitized resources are cataloged and documented to ensure transparency, traceability, and long-term usability. Table 1 presents a comprehensive inventory of the geological maps utilized in this project, illustrating both the breadth and depth of the available cartographic resources. Each catalog entry includes essential metadata such as map type, publication year, cartographic scale, and the key geological features represented (e.g., lithological units, folds, and fault systems).

This level of detailed documentation ensures accurate attribution of data sources and facilitates systematic review, reuse, and validation by other researchers and stakeholders. By establishing a well-curated and accessible digital bibliography, the project adheres to principles of scientific rigor, reproducibility, and data integrity. Consequently, the geological assessments and value-added products generated within the SUTGMM framework are grounded in a robust and verifiable data foundation, enhancing both their credibility and long-term relevance.

Table 1: List of the maps used in the project.

Publisher	Date	Map Type	No.	Title	Scale	Unlocking Data
Geological Survey of Iran	1983	Geological Quadrangle Map of Iran	M14	Pishin	1:250,000	Map
Geological Survey of Iran	1983	Geological Quadrangle Map of Iran	M13	Saravan	1:250,000	Map
Geological Survey of Iran	1983	Geological Quadrangle Map of Iran	K14	Fannuj	1:250,000	Map
Geological Survey of Iran	1989	Geological Quadrangle Map of Iran	L14	Nikshahr	1:250,000	Map
Geological Survey of Iran	1994	Geological Quadrangle Map of Iran	8041	Kahir	1:100,000	Fold, Fault, Legend, etc.
Geological Survey of Iran	1995	Geological Quadrangle Map of Iran	8042	Nik Shahr	1:100,000	Map
Geological Survey of Iran	1996	Geological Quadrangle Map of Iran	8140	Chabahar	1:100,000	Fold, Fault, Legend, etc.
Geological Survey of Iran	2004	Geological Quadrangle Map of Iran	8142	Qasr-e-Qand	1:100,000	Map
Geological Survey of Iran	2004	Geological Quadrangle Map of Iran	8141	Pirsohrab	1:100,000	Fold, Fault, Legend, etc.

1.5 Scope and Data Collection

The scope of this project encompasses the identification, organization, and utilization of existing geoscience data related to the Makran Zone within the framework of the SUTGMM Programme. Specifically, the project includes the systematic inventory of geoscientific data assets held by governmental organizations, academic institutions, and industry stakeholders. This inventory aims to document data types, formats, ownership, accessibility, and current levels of use.

The project further covers data discovery and metadata enrichment activities designed to surface hidden, poorly documented, or underutilized datasets, including geological maps, borehole and drilling records, geophysical datasets, and remote sensing products. To enable effective reuse, standardized metadata will be developed and applied, capturing spatial references, data provenance, quality indicators, and usage constraints.

Another core component of the scope is the design and implementation of data integration workflows. These workflows include data cleaning, normalization, geospatial alignment, and schema harmonization, along with mechanisms for provenance and trust tracking to ensure transparency and reproducibility of analytical outputs.

In addition, the project includes the development and application of lightweight analytical tools and geovisualization products tailored to the needs of geologists, policymakers, and other decision-makers. All workflows, tools, and analytical pipelines will be documented and accompanied by training materials to support reproducibility and knowledge transfer. Deployment and testing of these components will take place within the existing SUTGMM information and knowledge-base (ICT/KB) infrastructure.

The scope of the present project is defined by a structured, phased approach to activating existing geoscience assets within the Makran Zone under the operational framework of the SUTGMM Programme. The emphasis is placed on systematic identification, controlled integration, and analytically meaningful reuse of pre-existing datasets rather than on primary data acquisition. Accordingly, the project delineates clear boundaries with respect to thematic coverage, spatial extent, institutional engagement, and technological deployment.

At the core of the scope is a comprehensive data inventory process. This process encompasses the identification of geoscientific datasets maintained by governmental agencies (e.g., geological surveys and mineral resource authorities), academic research centers, and relevant industry actors engaged in exploration or infrastructure development. The inventory will not merely list available datasets; it will document their structural attributes, including data type (e.g., vector, raster, tabular, report-based), thematic domain (e.g., lithostratigraphy, structural geology, geophysics), scale or resolution, temporal coverage, coordinate reference system, custodial ownership, access conditions, and current operational use.

This inventory phase serves multiple strategic objectives. First, it establishes a transparent baseline of available assets within the Makran Zone. Second, it enables gap analysis by identifying thematic redundancies, spatial inconsistencies, or underrepresented domains. Third, it clarifies governance conditions, including data-sharing restrictions, intellectual property considerations, and institutional responsibilities. The resulting inventory will function as a structured catalogue integrated into the SUTGMM ICT/KB infrastructure, forming the foundation for subsequent integration workflows.

Beyond formal datasets, the scope explicitly includes the discovery and activation of hidden or poorly documented data resources. These may include legacy geological maps lacking digital vector formats, borehole and drilling records archived in scanned reports, geophysical line data stored in proprietary formats, laboratory geochemical analyses embedded in academic theses, and remote sensing derivatives generated for project-specific applications. Particular attention will be given to materials that possess high interpretive value but remain operationally inaccessible due to insufficient metadata, unclear provenance, or limited digital standardization.

Metadata enrichment constitutes a central methodological component of data collection. For each dataset selected for integration, standardized metadata schemas will be applied in alignment with recognized geospatial and data governance standards. These schemas will capture:

- Spatial reference information (projection, datum, coordinate system, spatial accuracy);
- Temporal attributes (date of acquisition, revision history, versioning);
- Data provenance (source institution, authoring entity, methodological description);
- Quality indicators (resolution, uncertainty estimates, validation status);
- Usage constraints (licensing terms, access restrictions, citation requirements);
- Processing history (transformations, cleaning steps, normalization procedures).

The development of such structured metadata not only enhances discoverability but also ensures analytical traceability, thereby strengthening reproducibility and scientific credibility.

The scope further encompasses the design and operationalization of data integration workflows tailored to the heterogeneous nature of Makran-related datasets. These workflows will incorporate several sequential stages:

1. **Data Cleaning:** Removal of redundancies, correction of geometric inconsistencies, elimination of topological errors, and verification of attribute completeness.

2. **Normalization:** Standardization of classification systems, stratigraphic nomenclature, lithological codes, and structural descriptors to ensure semantic coherence across datasets.

3. **Geospatial Alignment:** Harmonization of coordinate systems and spatial referencing, including reprojection to unified frameworks and alignment with authoritative base layers such as digital elevation models or administrative boundaries.

4. **Schema Harmonization:** Design of relational data models capable of integrating lithological, structural, geochemical, and geophysical attributes within interoperable database structures.

5. **Provenance and Trust Tracking:** Implementation of mechanisms to document data lineage, transformation history, and confidence levels, thereby supporting transparent interpretation and auditability.

These workflows will be implemented within the SUTGMM server-based architecture, enabling controlled ingestion, version management, and secure storage of integrated datasets. The project does not aim to establish a full-scale enterprise geodata platform; rather, it focuses on a modular, lightweight implementation optimized for pilot-scale demonstration and iterative enhancement.

In addition to data integration, the project scope includes the development of targeted analytical and visualization outputs designed to meet the needs of multiple stakeholder groups. For geoscientists, this may include interactive thematic layers, stratigraphic correlation visualizations, and fault-network overlays. For policymakers and planners, geovisualization products may highlight hazard-prone zones, resource distribution patterns, or land-use constraints derived from integrated geological information. Analytical tools will emphasize exploratory and decision-support functionalities rather than computationally intensive modeling, thereby maintaining alignment with the lightweight architecture of the SUTGMM infrastructure.

All developed workflows, data models, and analytical pipelines will be systematically documented. Documentation will include technical descriptions of processing steps, metadata standards applied, database schema definitions, and user-oriented guidance for data access and visualization. Complementary training materials—such as workflow diagrams, procedural manuals, and demonstration case examples—will be prepared to facilitate institutional adoption and knowledge transfer. This ensures that the project's outputs are not limited to a single implementation instance but can be replicated or adapted in comparable geological contexts.

Deployment and validation of all components will occur within the existing SUTGMM ICT and knowledge-base infrastructure. Pilot testing in selected sub-areas of the Makran Zone will assess system performance in terms of data ingestion efficiency, metadata completeness, interoperability, visualization responsiveness, and user accessibility. Feedback mechanisms will be incorporated to iteratively refine workflows and metadata schemas.

Through this clearly bounded yet comprehensive scope, the project operationalizes a structured pathway for transforming dispersed geoscience assets into coherent, interoperable, and decision-supportive knowledge layers. By prioritizing inventory, standardization, integration, and usability within an established ICT framework, the initiative advances both the technical robustness and practical relevance of geological data management in the Makran Zone.

1.5.1 Out of Scope

The project explicitly excludes the development of a full-scale, production-grade Earth data platform beyond the proposed pilot implementations. It does not involve the acquisition of new geoscience data through field surveys, drilling, or geophysical campaigns, focusing instead on the cataloging, integration, and reuse of existing datasets.

Furthermore, while the project will ensure compliance with relevant geoscience data policies, ethical standards, and access regulations, it does not encompass legal negotiations, contractual arrangements, or policy reforms that fall outside the defined scope of the research.

In addition, the project does not seek to replace or supersede existing national or institutional geospatial infrastructures. The SUTGMM implementation is conceived as a complementary, pilot-scale framework designed to demonstrate methodological feasibility and value activation within a defined geographic and thematic boundary. As such, it does not aim to centralize all institutional data holdings, enforce mandatory data-sharing policies, or restructure established governance models. Institutional autonomy over data custodianship and decision-making authority remains fully preserved.

The scope also excludes the long-term operational maintenance of enterprise-level information systems beyond the project lifecycle. While workflows, schemas, and documentation will be designed to support continuity and scalability, sustained infrastructure hosting, enterprise cybersecurity management, and national-scale system deployment fall outside the current research mandate. The project's outputs are therefore positioned as demonstrative and transferable components rather than permanent production infrastructure.

From a methodological standpoint, the initiative does not attempt to produce definitive or legally binding geological maps intended for regulatory certification, mining licensing, or formal land-use adjudication. The unified thematic products generated under the SUTGMM workflow are research-grade outputs designed to support analytical exploration, hypothesis generation, and decision-support visualization. Any subsequent formal adoption for statutory or regulatory purposes would require independent validation and institutional endorsement beyond the research framework.

The project similarly excludes advanced, resource-intensive modeling efforts such as basin-scale 3D seismic inversion, probabilistic seismic hazard modeling at engineering design resolution, or quantitative mineral reserve estimation compliant with international reporting standards. While the integrated datasets may provide foundational inputs for such analyses in future initiatives, the present scope is limited to lightweight analytics, thematic harmonization, and server-based geovisualization suitable for pilot demonstration.

Moreover, the project does not extend to the digitization and integration of all possible ancillary datasets related to the Makran Zone. Highly specialized datasets—such as proprietary industrial seismic lines, confidential exploration data, or restricted defense-related geospatial information—will only be considered where lawful access and explicit authorization are granted. The research does not undertake negotiations to secure access to restricted datasets nor does it assume responsibility for resolving institutional access disputes.

In terms of geographic coverage, while the Makran Zone constitutes the primary case study area, the project does not aim to achieve exhaustive spatial completeness at all cartographic scales. Data integration efforts will prioritize available and accessible datasets within the defined pilot boundaries. Areas with incomplete or low-quality data coverage will be transparently documented rather than artificially interpolated to create the appearance of continuity.

Finally, the project does not encompass policy reform initiatives related to national open-data legislation, intellectual property frameworks, or cross-border geoscience data-sharing agreements. Although the workflow will adhere to applicable standards for metadata documentation, citation, and responsible data use, broader regulatory transformations remain beyond the academic and technical objectives of this research.

By articulating these exclusions explicitly, the project delineates a focused and manageable operational boundary.

This clarity ensures that objectives remain aligned with the core mission of activating, harmonizing, and demonstrating the analytical potential of existing geoscience datasets within a structured SUTGMM pilot environment, without extending into institutional, legal, or infrastructural domains that exceed the defined research scope.

1.6 Workflow and Protocol for Server-Based Unified Thematic Geological Mapping (SUTGMM)

The Server-Based Unified Thematic Geological Mapping (SUTGMM) workflow for the Makran Zone is designed as a reproducible, iterative, and data-integrative protocol that leverages multi-source remote sensing datasets and machine-learning techniques within a centralized server-based environment. The approach emphasizes systematic data integration, transparency, and scalability, consistent with the objectives of unlocking and operationalizing existing geoscience data assets.

The workflow begins with the ingestion and preprocessing of heterogeneous Earth observation datasets, including Sentinel-1 SAR, Sentinel-2 multispectral imagery, Landsat-8 optical data, ASTER products, and Shuttle Radar Topography Mission (SRTM) digital elevation models. Feature extraction procedures are applied to derive spectral, textural, topographic, and structural indicators relevant to lithological discrimination and tectonic interpretation. These features are harmonized spatially and thematically to ensure consistency across sensors and resolutions.

Supervised machine-learning classification is subsequently employed to generate preliminary thematic geological units. Training datasets are derived from existing geological maps, expert interpretations, and verified field observations. The classification results undergo systematic field validation and expert review, enabling the identification of misclassifications and uncertainty patterns. Feedback from field checking is iteratively incorporated into model refinement, feature selection, and rule adjustment, enhancing both accuracy and geological plausibility.

The final stage of the workflow integrates the refined thematic outputs into a unified geospatial framework. Deliverables include a server-based unified geological map, associated structural sections, and an integrated geodatabase containing harmonized raster and vector layers with documented metadata and provenance. This protocol supports dynamic updating, reproducible analyses, and downstream applications such as regional synthesis, hazard assessment, and resource potential evaluation within the SUTGMM infrastructure.

The Server-Based Unified Thematic Geological Mapping (SUTGMM) workflow implemented for the Makran Zone is structured as a modular, reproducible, and iterative protocol designed to operate within a centralized server-based geospatial environment. The workflow integrates multi-source Earth observation data, legacy geological information, and supervised machine-learning methodologies to produce harmonized thematic geological outputs. Emphasis is placed on methodological transparency, traceable data lineage, scalability across spatial scales, and compatibility with the broader SUTGMM ICT/KB infrastructure.

1.6.1 Data Ingestion and Preprocessing

The workflow is initiated through the controlled ingestion of heterogeneous remote sensing and topographic datasets into the server environment. Core data sources include Sentinel-1 Synthetic Aperture Radar (SAR), Sentinel-2 multispectral imagery, Landsat-8 Operational Land Imager (OLI) data, ASTER multispectral and thermal products, and Shuttle Radar Topography Mission (SRTM) digital elevation models. These datasets collectively provide complementary spectral, structural, and morphometric information suitable for lithological discrimination and tectonic feature detection.

Preprocessing procedures are standardized to ensure cross-sensor comparability and analytical integrity. For optical imagery (Sentinel-2, Landsat-8, ASTER), steps include radiometric calibration, atmospheric correction, cloud masking, mosaicking, and resampling to a unified spatial resolution where appropriate. For SAR datasets (Sentinel-1), preprocessing includes orbit correction, radiometric calibration, speckle filtering, terrain correction, and conversion to backscatter coefficients. Digital elevation models undergo void filling, hydrological conditioning, and derivation of secondary terrain attributes.

All datasets are georeferenced to a unified coordinate reference system defined for the Makran Zone and stored within a version-controlled server-based geodatabase. Metadata are generated concurrently, documenting acquisition parameters, preprocessing algorithms, software versions, and quality indicators to ensure reproducibility.

1.6.2 Feature Extraction and Harmonization

Following preprocessing, a multi-tiered feature extraction phase is conducted. This stage transforms raw spectral and topographic data into analytically meaningful indicators relevant to geological mapping. Extracted features include:

- **Spectral indices:** band ratios and composite indices sensitive to iron oxides, clay minerals, carbonates, and silicate minerals;
- **Textural metrics:** grey-level co-occurrence matrix (GLCM)–based measures derived from optical and SAR data to capture surface roughness and structural patterns;
- **Topographic derivatives:** slope, aspect, curvature, relative relief, topographic position index (TPI), and drainage density derived from SRTM data;
- **Structural indicators:** lineament density maps, directional filters, and radar backscatter anisotropy analyses highlighting fault zones and fold axes.

These features are spatially harmonized through resampling, normalization, and co-registration procedures to ensure alignment across varying spatial resolutions and sensor characteristics. Thematic harmonization is achieved by organizing features within a structured data model that groups variables according to geological relevance (e.g., lithological indicators, structural proxies, geomorphological controls).

Feature scaling and dimensionality reduction techniques—such as principal component analysis (PCA) or feature importance ranking—may be applied to reduce redundancy and improve computational efficiency while preserving geological interpretability.

1.6.3 Training Data Preparation and Supervised Classification

Supervised machine-learning classification constitutes the core analytical component of the SUTGMM workflow. Training datasets are derived from multiple sources: digitized legacy geological maps, verified field observations, expert-delineated polygons, and, where available, borehole or lithological point records. Training samples are subjected to quality screening to ensure spatial accuracy, class consistency, and adequate representation of lithological variability.

Selected machine-learning algorithms may include Random Forest (RF), Support Vector Machines (SVM), Gradient Boosting, or other ensemble classifiers suitable for high-dimensional geospatial data. Model selection is guided by performance metrics, interpretability, and computational efficiency within the server environment.

The classification process produces preliminary thematic units representing lithological classes or structurally controlled domains. Model performance is evaluated using cross-validation techniques and statistical metrics such as overall accuracy, producer's and user's accuracy, F1-score, and confusion matrices. Uncertainty surfaces and probability layers are generated to spatially represent classification confidence and identify zones requiring further validation.

1.6.4 Iterative Field Validation and Model Refinement

A defining characteristic of the SUTGMM protocol is its iterative validation mechanism. Preliminary classification outputs are subjected to systematic field verification and expert review. Field campaigns focus on transitional boundaries, structurally complex zones, and areas with high model uncertainty.

Field observations—including lithological descriptions, structural measurements, and geotagged photographic records—are ingested into the server-based system in near real-time or post-campaign synchronization. Discrepancies between predicted and observed classes are analyzed to identify systematic misclassification patterns, feature insufficiencies, or training data imbalances.

Model refinement may involve:

- Adjustment of class definitions or merging/splitting of thematic units;
- Enhancement of training datasets;
- Inclusion of additional spectral or structural features;
- Parameter tuning or algorithm substitution.

This feedback loop strengthens both statistical robustness and geological plausibility, ensuring that automated outputs remain grounded in expert knowledge and empirical verification.

1.6.5 Integration within the Unified Geospatial Framework

Upon completion of iterative refinement, finalized thematic outputs are integrated into a unified geospatial framework within the SUTGMM infrastructure. Deliverables include:

- A server-hosted unified thematic geological map of the Makran Zone;
- Associated structural overlays (fault traces, fold axes, lineament networks);
- Derived geomorphological and morphotectonic layers;
- An integrated geodatabase containing harmonized raster and vector datasets with fully documented metadata and provenance records.

All layers are stored in interoperable formats and made accessible through standardized geospatial services (e.g., Web Map Services, Web Feature Services) where permitted by data governance policies. Version control mechanisms track updates, enabling dynamic revision as new data or field validations become available.

1.6.6 Reproducibility, Transparency, and Scalability

A central objective of the SUTGMM workflow is methodological reproducibility. Each processing stage—data ingestion, preprocessing, feature extraction, classification, validation, and integration—is documented through structured workflow scripts, parameter logs, and metadata records. This ensures that analytical outputs can be replicated, audited, or extended by other researchers within the same infrastructure.

The server-based architecture supports scalability across spatial extents and thematic domains. While initially implemented for the Makran Zone, the protocol can be adapted to other tectonically complex regions by substituting input datasets and retraining classification models within the same framework.

Through this structured and iterative workflow, the SUTGMM protocol operationalizes a transition from fragmented data layers toward an integrated, analytically robust, and dynamically updateable geological mapping system. By combining remote sensing analytics, machine learning, and expert-driven validation within a centralized environment, the approach delivers a transparent and scalable methodology for unified thematic geological mapping aligned with the strategic objectives of data activation and sustainable geoscience knowledge management.

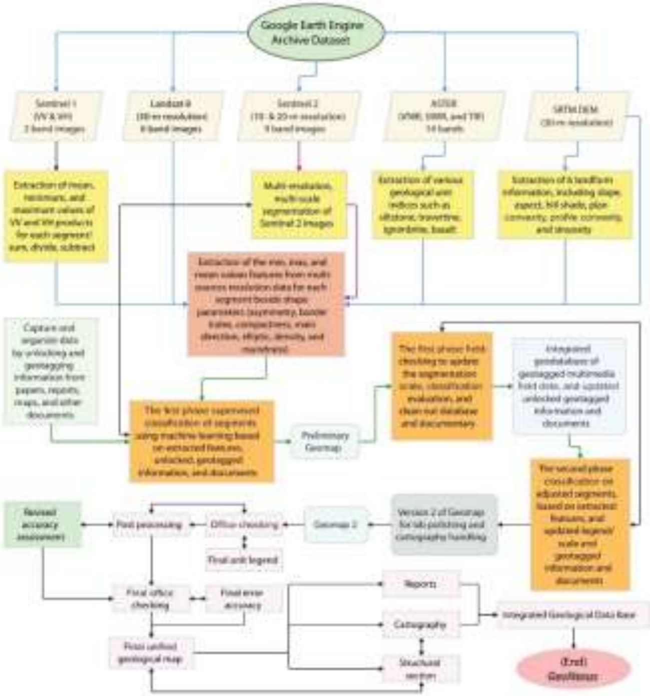


Figure 9. Workflow and protocol for Server-based Unified Thematic Geological Mapping of Makran (SUTGMM) using multi-source remote sensing data and machine learning. The process includes feature extraction from Sentinel-1, Sentinel-2, Landsat 8, ASTER, and SRTM DEM data, supervised classification, field-checking, and iterative refinement. The final outputs include a unified geological map, structural section, and integrated geodatabase

1.7 Objectives

1.7.1 Primary Objective

The primary objective of this project is to design, implement, and demonstrate an end-to-end framework for identifying, curating, integrating, and analyzing trapped or underutilized geoscientific data within the SUTGMM ecosystem. The framework aims to transform existing data assets into high-value geological insights and decision-support products for the Makran Zone within a one-year timeframe, without reliance on new data acquisition campaigns.

This objective is grounded in the premise that significant scientific and strategic value resides in legacy geological maps, archived reports, remote sensing products, borehole records, and related datasets that remain only partially integrated into contemporary analytical workflows. By focusing on data activation rather than data expansion, the project seeks to demonstrate that improved governance, harmonization, and computational integration can yield substantial enhancements in interpretive capacity, decision-support functionality, and reproducibility.

Operationally, the primary objective encompasses four interdependent dimensions:

1. Systematic Data Identification and Curation: Establishing structured procedures for cataloging available datasets, evaluating their relevance and quality, and organizing them within a coherent metadata-driven inventory. This includes formalizing selection criteria, documenting provenance, and prioritizing datasets based on thematic importance and integration feasibility.

2. Standardized Integration within the SUTGMM Architecture:
Designing and deploying reproducible workflows for data cleaning, normalization, geospatial alignment, and schema harmonization. The objective is to ensure that previously isolated datasets become interoperable components of a unified geodatabase hosted within the SUTGMM server environment.

3. Analytical Activation and Thematic Synthesis:

Applying lightweight analytical techniques—including feature extraction, supervised classification, spatial overlay analysis, and uncertainty mapping—to transform curated datasets into coherent thematic outputs. These outputs are intended to enhance lithological discrimination, structural interpretation, and regional geological synthesis within the Makran Zone.

4. Delivery of Decision-Support and Visualization Products:
Generating accessible geovisualization layers, integrated geological maps, and supporting documentation tailored to researchers, institutional stakeholders, and regional planners. The objective is not only to produce maps, but to create dynamic, queryable, and updateable knowledge products that support evidence-based planning and scientific inquiry.

The one-year timeframe imposes a structured implementation schedule emphasizing phased deployment, iterative refinement, and demonstrable outputs. Rather than pursuing large-scale infrastructural development, the project prioritizes proof-of-concept validation within the Makran Zone. Success is measured by the operational readiness of the

SUTGMM framework, the completeness and interoperability of integrated datasets, and the generation of analytically meaningful geological products derived exclusively from pre-existing data resources.

Importantly, the objective extends beyond technical integration to encompass methodological transparency and reproducibility. Each stage of the framework—from inventory and metadata enrichment to thematic mapping and analytical synthesis—will be documented through standardized protocols, version-controlled workflows, and traceable data lineage records. This ensures that outputs are auditable, replicable, and transferable to other regions characterized by similar data fragmentation challenges.

By achieving this primary objective, the project aims to demonstrate that trapped geoscientific data, when systematically curated and integrated within a structured server-based ecosystem, can be transformed into actionable geological intelligence. In doing so, it provides a scalable model for cost-effective digital transformation in the geosciences, aligned with sustainable development imperatives and modern principles of data governance.

1.7.2 Secondary (Specific) Objectives

In support of the primary objective, the project advances a set of secondary objectives that operationalize methodological rigor, domain specificity, and practical validation within the SUTGMM framework. These objectives collectively strengthen the institutional, analytical, and governance dimensions of geoscience data activation in the Makran Zone.

The secondary objectives of the project are as follows:

- To establish repeatable and domain-specific data curation and governance practices tailored to geoscience datasets, including seismic, magnetotelluric, geological mapping, borehole, geochemical, and satellite-based remote sensing data.

- To develop scalable and reproducible data integration pipelines capable of transforming heterogeneous geoscience datasets into actionable geological products, such as thematic geological maps, three-dimensional subsurface models, probabilistic resource assessments, and interactive dashboards.

- To validate the scientific and practical value of the proposed framework through two pilot use cases in the Makran Zone: (i) integrated tectonic and structural mapping, and (ii) mineral potential assessment and soil/geochemical screening.

- To define and document ethical, privacy, and data governance guidelines specific to geospatial and sensitive geoscience data, addressing issues of data ownership, access control, usage conditions, transparency, and responsible reuse within the SUTGMM Programme.

Chapter 2: Theoretical Foundations and Literature Review

2.1 The Concept of Trapped Data

Trapped data refers to datasets that exist and possess high potential value but remain inaccessible or underutilized due to governance, technical, or institutional constraints. In geoscience, such data often accumulates across decades without systematic integration.

2.1.1 Establishment of Domain-Specific Data Curation and Governance Practices

A central secondary objective is the formulation of repeatable and geoscience-tailored data curation protocols applicable to diverse dataset categories, including seismic reflection and refraction data, magnetotelluric (MT) surveys, geological mapping products, borehole and drilling logs, laboratory-based geochemical analyses, and satellite-derived remote sensing datasets.

Given the heterogeneity of these data types—ranging from raster grids and vector polygons to time-series waveforms and tabular analytical results—the project will define structured curation practices addressing:

- Data format standardization and conversion;
- Metadata schema harmonization aligned with geospatial and scientific standards;
- Controlled vocabularies for lithology, stratigraphy, and structural descriptors;
- Quality grading and uncertainty documentation;
- Version control and archival traceability mechanisms.

These practices will be codified into operational guidelines embedded within the SUTGMM ICT/KB environment, enabling consistent data onboarding and lifecycle management. The objective is not only to curate datasets for the Makran pilot, but to establish a transferable governance template adaptable to other geoscientific domains and regions.

2.1.2 Development of Scalable and Reproducible Data Integration Pipelines

Another key objective is the design and implementation of modular, scalable, and reproducible data integration pipelines capable of converting heterogeneous geoscience datasets into actionable analytical products. These pipelines will incorporate structured workflows for preprocessing, normalization, spatial harmonization, attribute alignment, and cross-thematic synthesis.

The integration architecture will support the generation of multiple classes of geological outputs, including:

- Unified thematic geological maps derived from multi-source inputs;
- Three-dimensional conceptual subsurface models integrating structural, borehole, and geophysical constraints;
- Probabilistic mineral prospectivity and resource potential maps using spatial statistical approaches;
- Interactive dashboards and geovisualization platforms enabling user-driven exploration of harmonized datasets.

Scalability will be ensured through modular pipeline design, allowing substitution of input datasets or expansion to additional geographic extents without restructuring the entire system. Reproducibility will be reinforced through documented processing scripts, parameter logs, and standardized metadata protocols.

This objective ensures that integration processes remain transparent, auditable, and transferable beyond the immediate pilot context.

2.1.3 Validation through Pilot Use Cases in the Makran Zone

- To demonstrate scientific credibility and applied relevance, the framework will be tested through two targeted pilot use cases within the Makran Zone.

- (i) Integrated Tectonic and Structural Mapping: This uses case will focus on synthesizing remote sensing derivatives, legacy geological maps, digital elevation models, and structural datasets to refine interpretations of fault systems, fold geometries, and tectonic domains. The integration process will evaluate improvements in spatial coherence, boundary delineation accuracy, and uncertainty characterization relative to existing mapping products.

- (ii) Mineral Potential Assessment and Soil/Geochemical Screening:
  The second use case will combine lithological layers, structural indicators, geochemical sampling results, and terrain derivatives to generate exploratory mineral prospectivity maps. Statistical or machine-learning–based spatial modeling techniques will be employed to identify

favorable zones, while maintaining explicit uncertainty documentation.

Together, these pilot implementations will serve as empirical validation mechanisms, demonstrating how curated and harmonized data assets can enhance interpretive resolution, reduce analytical redundancy, and support evidence-based exploration and planning.

2.2 Data Governance in Geosciences

Data governance encompasses policies, roles, standards, and procedures that regulate data lifecycle management. In geological organizations, governance must address:

- Data ownership and stewardship
- Access control mechanisms
- Metadata standardization
- Long-term preservation and provenance tracking

Particular attention will be paid to the ethical implications of integrating subsurface data, mineral potential outputs, or geospatial layers that may influence land-use decisions. Clear documentation of usage constraints and disclaimers will accompany derived products to prevent misinterpretation or misuse.

- Integrated Contribution of Secondary Objectives
- Collectively, these secondary objectives reinforce the technical, scientific, and governance robustness of the SUTGMM framework. They ensure that the project moves

beyond proof-of-concept integration toward the establishment of structured best practices in geoscience data stewardship, scalable analytical design, and responsible knowledge dissemination.

- By embedding repeatable curation protocols, scalable pipelines, empirically validated use cases, and clearly articulated governance guidelines within the Makran pilot implementation, the project strengthens the credibility, adaptability, and long-term relevance of the SUTGMM Programme as a model for data-driven geological transformation.

2.2.1 Governmental Agencies

Governmental organizations constitute primary custodians of geoscience data for the Makran region. Key contributors include national geological surveys, mineral exploration departments, and environmental monitoring authorities. These agencies provide high-value datasets such as:

Published and unpublished geological maps at various scales (e.g., 1:250,000 and 1:100,000);

Borehole logs and stratigraphic profiles detailing lithology, subsurface structure, and hydrogeology;

Seismic reflection and refraction records, as well as magnetotelluric (MT) survey results;

Historical survey reports and interpretive documentation, often including georeferenced cross-sections and structural interpretations.

Data from governmental agencies frequently serve as authoritative reference layers for validation, training, and integration of other sources, forming the backbone of the SUTGMM inventory.

2.2.2 Academic Institutions

Universities and research centers provide complementary datasets derived from research-driven studies. These include:

Analyses of satellite imagery and remote sensing products;

Geochemical and mineralogical datasets obtained through laboratory investigations;

Structural and tectonic interpretations synthesized from field campaigns and analytical models;

Prior modeling studies, including 3D conceptual frameworks and regional-scale geodynamic simulations.

Academic data often provide additional resolution or thematic depth, particularly in areas not comprehensively covered by governmental surveys, and serve as critical inputs for feature extraction and supervised classification within the SUTGMM workflow.

2.2.3 Industry Stakeholders

Mining, hydrocarbon, and energy companies maintain exploration datasets that can offer high-resolution, site-specific geoscientific information, including:

Proprietary geophysical surveys (e.g., 2D/3D seismic lines, gravity, and magnetic data);

Detailed exploration reports, lithological logs, and resource assessments;

Data on mineral deposits, hydrocarbon prospects, and soil or geochemical sampling.

Access to industry data will be negotiated under confidentiality agreements where necessary, and sensitive information may be anonymized or aggregated to comply with corporate and legal restrictions while allowing analytical use.

2.3 Server-Based GIS Architectures

Server-based geospatial systems enable centralized storage, scalable processing, controlled access, and version management. Such architectures support collaborative workflows and reproducible analytics, making them suitable for national geological infrastructures.

2.3.1 Remote Sensing and Publicly Available Data

Open-access and publicly released datasets complement institutional and proprietary data sources. Key examples include:

Satellite imagery from Sentinel-1 SAR, Sentinel-2 multispectral, and Landsat series;

Digital elevation models (DEMs), such as SRTM or ASTER-derived terrain models;

Geospatial datasets relevant to environmental monitoring, land cover classification, or structural mapping.

These data provide spatially continuous and temporally updatable coverage, essential for feature extraction, thematic mapping, and validation of legacy data layers.

2.3.2 Data Stewardship and Accessibility Protocols

To ensure responsible and reproducible use, all datasets will undergo structured evaluation for ownership, licensing, access permissions, and usage constraints. Data stewardship within the SUTGMM framework will include:

Cataloging and Metadata Enrichment: Each dataset will be inventoried and described using standardized, domain-specific metadata schemas. Metadata will capture provenance, data quality indicators, units of measurement, spatial references, temporal coverage, and confidence levels. This ensures discoverability, traceability, and transparency of analytical outputs.

Access Control and Ethical Compliance: Access will be managed according to institutional policies and applicable legal and ethical standards. Sensitive or restricted datasets will be de-identified, aggregated, or converted into synthetic derivatives where appropriate to enable analytical use without compromising confidentiality or security.

Integration within the SUTGMM Infrastructure: Authorized datasets will be ingested into the centralized server-based SUTGMM knowledge base and ICT infrastructure. This ensures consistent availability for workflow execution, reproducible analyses, and visualization outputs, while maintaining version control and auditability of all data transformations.

By consolidating these diverse sources under a standardized governance framework, the project achieves two interrelated objectives: broad accessibility of data for integrated geoscientific analysis, and strict adherence to ethical, legal, and institutional requirements. This approach establishes a reliable foundation for subsequent stages of data integration, thematic mapping, and decision-support product generation within the Makran Zone.

2.4 Metadata Standards and Interoperability

Metadata frameworks ensure discoverability, interoperability, and reusability. International standards emphasize structured documentation of spatial reference systems, acquisition methods, data quality indicators, and lineage information.

2.4.1 Definition of Ethical, Privacy, and Data Governance Guidelines

A further secondary objective is the articulation of ethical and governance principles tailored to geospatial and potentially sensitive geoscience datasets. While the project does not undertake policy reform, it aims to document practical guidelines addressing:

- Data ownership clarification and attribution standards;
- Tiered access control models within the SUTGMM infrastructure;
- Responsible data-sharing practices;
- Transparency in analytical transformations and derived products;

- Management of confidential or commercially sensitive geoscience information.

2.4.2 Data Sources and Accessibility

The project will leverage existing geoscientific data assets related to the Makran Zone, encompassing multiple types, formats, and institutional origins. Key sources include:

- Governmental Agencies: National geological surveys, mineral exploration departments, and environmental monitoring authorities, providing geological maps, borehole logs, seismic and magnetotelluric data, and historical survey reports.
- Academic Institutions: Universities and research centers contributing satellite imagery analyses, geochemical datasets, structural interpretations, and prior modeling studies.
- Industry Stakeholders: Mining and energy companies offering exploration data, geophysical surveys, and resource assessment records, subject to confidentiality agreements.
- Remote Sensing and Publicly Available Data: Satellite-derived imagery, digital elevation models (DEMs), and publicly released geospatial datasets relevant to structural, lithological, and environmental analysis.

Figure 10: Ravar Terrain Aspect Map: Aspect map generated from the 10 m DEM of the Ravar study area. This morphometric layer captures slope direction patterns and provides supporting terrain characterization for geomorphological interpretation.

To ensure accessibility and compliance, all data will undergo formal evaluation regarding ownership, licensing, access permissions, and usage restrictions. Data stewardship protocols will be applied, including:

- Cataloging and Metadata Enrichment: All datasets will be inventoried and described using standardized, domain-specific metadata, capturing provenance, data quality, units, spatial references, and confidence levels.
- Access Control and Ethical Compliance: Data access will be managed in accordance with institutional policies and applicable legal and ethical standards. Where necessary, de-identified or synthetic versions of sensitive datasets will be

generated to enable analysis without compromising confidentiality or security.

- Integration within SUTGMM Infrastructure: Authorized datasets will be ingested into the SUTGMM knowledge base and ICT infrastructure, ensuring traceability, reproducibility, and consistent availability for pipeline development and stakeholder use.

By consolidating diverse data sources under a standardized governance and metadata framework, the project ensures both broad accessibility for analysis and strict adherence to ethical, legal, and institutional requirements.

The project will utilize a wide spectrum of pre-existing geoscientific data assets relevant to the Makran Zone, drawing upon multiple types, formats, and custodial origins to support a comprehensive and integrated analytical framework. The heterogeneity of these datasets—ranging from legacy maps and field-based measurements to satellite-derived imagery and geophysical surveys—necessitates structured evaluation, curation, and governance to enable effective reuse.

Chapter 3: Unlocking Trapped Data

3.1 Introduction UTD

Within the **Unlocking Trapped Data (UTD)** framework, geological maps of the Makran Zone function as foundational yet historically underutilized assets. Produced by the Geological Survey of Iran, these maps encapsulate critical information on lithology, stratigraphy, structural architecture, and geomorphology. However, their legacy analog and semi-digital formats have limited their interoperability and analytical integration, effectively rendering them "trapped" within static cartographic archives.

This project activates these datasets by systematically georeferencing and digitizing them, ensuring precise spatial alignment within modern GIS environments. Through this process, geological quadrangle maps—available at regional (1:250,000) and detailed (1:100,000) scales—are transformed into interoperable, multi-scale digital layers. The georeferencing and harmonization enable reliable overlay with geophysical surveys, remote sensing imagery, and geochemical datasets, thereby enhancing analytical coherence and interpretive accuracy.

By converting static cartographic products into spatially aligned, queryable digital datasets, the project demonstrates how legacy geological maps can be unlocked, integrated, and repurposed as core components of a server-based thematic mapping infrastructure under the SUTGMM Programme.

3.2 Georeferencing and Spatial Integration

The georeferencing process establishes a consistent spatial framework across datasets, allowing legacy maps to be accurately overlaid with complementary geoscience information. This includes:

- Geophysical Surveys: Seismic, gravity, and magnetic datasets can be directly correlated with mapped lithological and structural units, enabling integrated interpretation of subsurface architecture.
- Remote Sensing Products: Multi-spectral and radar imagery, terrain derivatives, and lineament extractions can be analyzed in conjunction with mapped geological boundaries to refine lithological discrimination and identify tectonically controlled geomorphology.
- Geochemical and Borehole Data: Point-based observations and analytical measurements can be spatially contextualized within mapped units, improving interpretive consistency and facilitating probabilistic resource assessments.

The resulting spatial coherence increases the reliability and reproducibility of analytical outputs and allows for dynamic cross-validation between independent datasets, effectively unlocking the latent scientific potential of previously isolated map sheets.

3.3 Thematic and Cartographic Classification

- Geological maps are systematically classified according to their thematic content and cartographic resolution, with particular emphasis on **Geological Quadrangle Maps.** These maps provide detailed representations of:

- Lithological units, including rock type, age, and compositional characteristics;

- Geological boundaries and contacts, defining stratigraphic and structural limits;

- Fault systems, lineaments, and fold axes, highlighting tectonic processes;

- Major structural and geomorphological features relevant to regional geodynamics and resource distribution.

Thematic classification ensures that maps can be selectively incorporated into workflows based on research questions, spatial scale requirements, and analytical objectives.

3.4 Multi-Scale Mapping for Regional and Local Analyses

The availability of geological maps at multiple cartographic scales is essential for addressing analyses across different spatial resolutions:

- Regional-Scale Mapping (1:250,000): Provides a synoptic view of lithological and structural patterns across the Makran Zone, supporting tectonic synthesis, regional resource evaluation, and hazard assessment.

- Detailed Mapping (1:100,000): Offers enhanced resolution suitable for localized studies, including site-specific structural analysis, mineral prospectivity assessments, and integration with field-verified geochemical data.

Multi-scale availability allows seamless scaling of analytical workflows, enabling researchers to transition from broad regional overviews to focused, high-resolution investigations without loss of spatial fidelity.

3.5 Unlocking Scientific Value through Integration

By georeferencing, classifying, and harmonizing these geological maps, the project converts “trapped” data into operationally accessible geoscientific assets. Key benefits include:

- Enhanced Analytical Interoperability: Georeferenced maps can be integrated with remote sensing derivatives, geophysical grids, and borehole records, facilitating multi-source synthesis.
- Improved Interpretive Accuracy: Spatial alignment reduces inconsistencies and allows for more precise delineation of lithological boundaries, faults, and structural domains.
- Support for Knowledge-Driven Applications: Maps form the backbone of thematic mapping, 3D conceptual modeling, mineral potential analysis, and hazard assessment within the SUTGMM environment.
- Reproducibility and Transparency: Standardized georeferencing, metadata enrichment, and cataloging enable traceable analyses and support long-term usability of the datasets by multiple stakeholders.

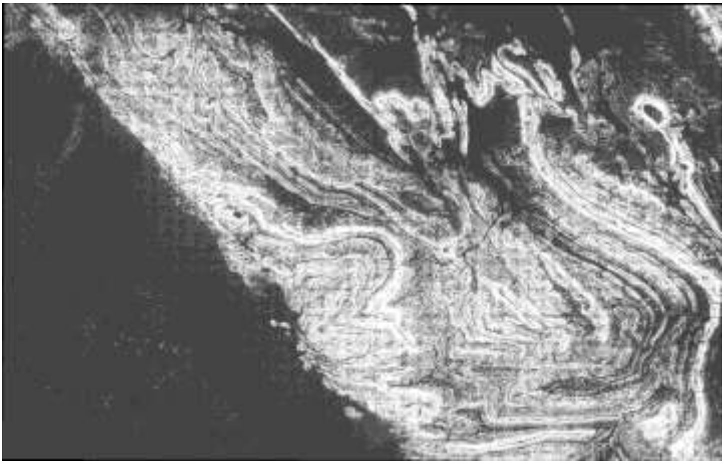


Figure 11: Full-Model K Prediction Map generated through integrated machine-learning analysis of harmonized terrain, radar, NDVI, and anthropogenic features, demonstrating the operationalization of previously trapped multi-source geospatial data within the SUTGMM

Through these processes, geological maps evolve from static reference documents into dynamic, integrable, and analytically actionable resources. This transformation exemplifies the broader objective of the SUTGMM Programme: to systematically unlock underutilized geoscientific data, maximize their interpretive potential, and generate high-value outputs for research, planning, and decision-making in the Makran Zone.

3.6 Unlocking Trapped Data (continued: Integration with Remote Sensing and Analytical Workflows)

Building upon the georeferenced geological maps, the project integrates these foundational datasets with complementary remote sensing and geophysical resources to enhance thematic resolution and interpretive depth within the Makran Zone. This integration transforms static maps into dynamic, multi-source geoscientific assets that support reproducible analysis, machine-learning classification, and structural interpretation.

3.6.1 Integration with Remote Sensing Data

Georeferenced maps are combined with satellite imagery and digital elevation models to generate additional geological insights:

- Multispectral and Hyperspectral Imagery: Sentinel-2, Landsat-8, and ASTER data provide spectral signatures indicative of surface mineralogy, weathering profiles, and lithological contrasts. By overlaying these data with mapped lithologies, spectral indices can be calibrated against known rock units, improving automated classification accuracy.
- Synthetic Aperture Radar (SAR): Sentinel-1 SAR imagery captures surface roughness, lineament orientations, and structural discontinuities that are often invisible in optical datasets. Georeferenced maps guide the interpretation of SAR-derived structural features, allowing identification of previously undocumented faults or folds.
- Digital Elevation Models (DEMs): High-resolution SRTM or ASTER DEMs support derivation of slope, aspect, curvature, and topographic position indices. When combined

with geological boundaries, these terrain metrics enhance structural mapping, geomorphological interpretation, and prediction of depositional environments.

The integration of these remote sensing derivatives with georeferenced geological maps enables consistent, spatially coherent multi-source analysis, improving the robustness of lithological, structural, and morphotectonic interpretations.

3.6.2 Machine-Learning Classification and Thematic Synthesis

The harmonized datasets serve as inputs for supervised machine-learning models designed to produce refined thematic geological layers:

- Training Data: Georeferenced geological maps provide the primary training polygons for lithological units, structural domains, and fault zones. Expert-curated field observations further validate training samples.
- Feature Extraction: Spectral, textural, topographic, and structural indices derived from remote sensing datasets form the feature space for classification. These features are aligned with map-based training units to maximize predictive accuracy.
- Iterative Classification: Supervised algorithms such as Random Forest or Support Vector Machines generate preliminary thematic units. Misclassifications are identified through cross-validation with geological maps and field data, and iterative feedback is used to refine model parameters, feature selection, and class definitions.

This process results in high-resolution thematic outputs that retain the interpretive validity of expert-compiled maps while incorporating spatially continuous, sensor-derived information.

3.6.3 Integration of Structural and Geophysical Data

Georeferenced maps also facilitate the incorporation of structural and geophysical datasets:

- Faults and Lineaments: Mapped faults guide the interpretation of lineament density and orientation derived from SAR, DEM, or magnetotelluric datasets, producing coherent structural overlays.
- Geophysical Surveys: Seismic reflection lines, gravity, and magnetic datasets are spatially aligned to the geological framework, allowing correlation of subsurface anomalies with mapped lithologies and structural domains.
- Borehole and Drill Data: Point-based subsurface observations are anchored to mapped units, supporting validation of machine-learning outputs and refining 3D conceptual models.

The integration of these diverse datasets generates a unified geospatial framework, combining lithological, structural, geophysical, and topographic information. This framework enables advanced applications such as 3D conceptual modeling, hazard assessment, and mineral potential mapping.

3.7 Metadata, Provenance, and Reproducibility

All integrated datasets are enriched with structured metadata capturing:

- Spatial references and projection systems;
- Source documentation and acquisition dates;
- Data quality metrics and confidence levels;
- Processing history and transformations applied.

This ensures traceability and reproducibility of analytical workflows, allowing users to understand the derivation of each thematic layer and supporting future updates as new data become available.

3.8 Outcome: Dynamic, Multi-Source Geological Knowledge

Through georeferencing, thematic classification, remote sensing integration, and structural/geophysical alignment, geological maps evolve from isolated, analog resources into dynamic, interoperable knowledge assets. These unified datasets form the core of the SUTGMM infrastructure, enabling:

- Multi-scale lithological and structural analyses;
- Probabilistic modeling of mineral potential and resource distribution;
- Evidence-based hazard assessment and environmental planning;
- Interactive geovisualization and stakeholder-oriented decision-support tools.

By systematically unlocking trapped data and embedding it within a server-based, multi-source framework, the project demonstrates how legacy geological maps can be transformed into high-value, actionable intelligence for scientific, institutional, and planning purposes in the Makran Zone.

3.9 Data Processing and Integration Workflows

Following the unlocking and georeferencing of legacy geological maps, the next phase of the project involves structured **data processing and integration workflows** designed to harmonize heterogeneous datasets within the SUTGMM infrastructure. These workflows operationalize the transition from raw or fragmented data to actionable geological outputs while ensuring reproducibility, traceability, and scalability.

3.9.1 Data Ingestion and Preprocessing

All datasets—including geological maps, remote sensing products, geophysical surveys, and borehole logs—are ingested into the centralized SUTGMM server environment. Preprocessing steps are tailored to data type:

- Raster Data (Satellite Imagery, DEMs): Radiometric calibration, atmospheric correction, cloud and shadow masking, resampling to uniform spatial resolution, and reprojection to the defined Makran Zone coordinate system.
- Vector Data (Geological Boundaries, Faults, Borehole Locations): Topological correction, simplification of complex geometries, attribute normalization, and alignment with georeferenced raster layers.

- Geophysical and Analytical Data: Conversion from proprietary formats, unit standardization, noise filtering, and georeferencing relative to mapped units.

Preprocessing ensures spatial and thematic consistency, reduces artifacts, and prepares datasets for integrated analysis. Automated scripts and server-based batch processing guarantee reproducibility and efficiency across large datasets.

3.10 Metadata Enrichment and Data Cataloging

For each ingested dataset, structured metadata is generated and stored in the SUTGMM knowledge base. Metadata records capture:

- Provenance information (origin institution, acquisition date, responsible personnel);
- Spatial and temporal coverage;
- Data type, format, and resolution;
- Quality indicators and confidence levels;
- Processing history and transformation logs.

This step facilitates discoverability, ensures proper attribution, and provides users with transparent documentation to support reproducible analyses and traceable decision-making.

3.11 Data Harmonization and Normalization

Heterogeneous datasets are standardized to enable interoperability:

- Attribute Harmonization: Lithological, structural, and geochemical classifications are unified using controlled vocabularies and standard nomenclatures.
- Spatial Alignment: Raster and vector layers are co-registered to a common projection, and discrepancies in boundary locations are reconciled using reference features from high-accuracy DEMs or field-validated points.
- Resolution Normalization: Multi-scale datasets are resampled or aggregated to maintain consistent spatial granularity suitable for both regional and local analyses.

Harmonization ensures that all datasets can be analyzed in combination, avoiding conflicts due to inconsistent terminologies, coordinates, or units.

Chapter 4: Integrated Analytical SUTGMM Framework and Outputs for Unlocking Trapped Data

4.1 Feature Extraction and Analytical Preparation

Geospatial and analytical features are derived from raw and harmonized data to serve as inputs for classification, modeling, and mapping:

- Spectral Features: Band ratios, vegetation indices, and mineral-sensitive indices derived from multispectral and hyperspectral imagery.
- Textural Features: Grey-level co-occurrence metrics and surface roughness measures extracted from SAR and optical imagery.
- Structural Features: Lineament density, fault orientation, curvature, slope, and topographic position metrics derived from DEMs and fault maps.
- Geochemical and Subsurface Features: Point-based analytical values interpolated or contextualized within mapped lithologies for predictive modeling.

Feature extraction creates a structured dataset ready for integration into supervised classification, spatial modeling, and thematic synthesis.

4.2 Data Integration and Unified Framework Construction

All preprocessed, harmonized, and feature-enriched datasets are integrated into a **centralized SUTGMM geospatial framework**, resulting in a unified environment for analysis:

- Raster and Vector Integration: Thematic raster layers, DEM derivatives, and vector polygons (geological boundaries, faults, boreholes) are linked through spatial indexing and relational database structures.

- Provenance Tracking: Each integrated dataset retains metadata linking it to its source, processing history, and quality assessments.
- Multi-Scale Compatibility: Both regional-scale and detailed datasets are incorporated with mechanisms to query and extract subsets for different analytical resolutions.

This unified framework enables cross-layer analysis, supporting workflows such as overlay modeling, structural interpretation, and resource potential mapping.

4.3 Iterative Validation and Quality Control

Data integration is accompanied by rigorous validation and quality control:

- Consistency Checks: Alignment of geological boundaries, fault traces, and lithological units across multiple sources.
- Cross-Validation: Verification of remote sensing–derived classifications against georeferenced maps and field observations.
- Uncertainty Mapping: Spatial identification of areas with high disagreement or data sparsity, guiding subsequent refinement or targeted validation efforts.

Iteration ensures that integrated datasets are both scientifically robust and operationally reliable for downstream applications.

4.4 Preparation for Analytical Outputs

The final step in the workflow prepares datasets for thematic mapping, machine-learning classification, and geovisualization:

- Datasets are structured into server-accessible layers, with standardized naming conventions, metadata, and documentation.

- Feature matrices for supervised classification are exported in consistent formats with linked training datasets derived from georeferenced maps and field-verified observations.

- Analytical workflows, including raster overlay, spatial modeling, and classification scripts, are version-controlled and stored within the SUTGMM infrastructure for reproducibility.

4.4.1 Outcome: Integrated, Actionable Geoscience Data

The completion of these workflows produces a **cohesive, multi-source, and harmonized geospatial framework** for the Makran Zone, serving as the foundation for:

- Unified thematic geological mapping;

- Structural and tectonic interpretation;

- Mineral potential modeling and geochemical screening;

- Interactive geovisualization and decision-support applications.

By systematically processing, harmonizing, and integrating diverse geoscientific datasets, the project operationalizes trapped data, unlocking latent analytical potential and enabling evidence-based planning and scientific exploration.

4.4.2 Analytical Outputs and Geovisualization Products

Following the systematic processing and integration of geoscientific datasets within the SUTGMM framework, the project produces **analytical outputs and geovisualization products** that transform raw and legacy data into actionable geological knowledge. These outputs are designed to be scientifically robust, reproducible, and operationally useful for research, institutional decision-making, and regional planning in the Makran Zone.

4.5 Unified Thematic Geological Maps

The primary deliverable consists of **unified thematic geological maps** generated from the integration of georeferenced legacy maps, remote sensing derivatives, and field-validated observations. Key features include:

- Lithological Units: Harmonized representation of rock types, age relationships, and compositional classes.
- Structural Elements: Consolidation of faults, lineaments, fold axes, and tectonic boundaries from multiple data sources.
- Stratigraphic Relationships: Spatially coherent depiction of stratigraphic contacts and depositional sequences.
- Multi-Scale Compatibility: Maps produced at 1:250,000 and 1:100,000 scales to support both regional synthesis and localized studies.

These maps provide a comprehensive, multi-source visualization of the Makran Zone's geology, suitable for integration into decision-support tools, academic research, and resource planning.

4.6 Three-Dimensional Conceptual and Subsurface Models

The project produces **3D conceptual models** by integrating surface geological maps, structural interpretations, borehole logs, and geophysical datasets:

- Subsurface Architecture: Visualization of stratigraphic layers, lithological units, and structural geometries in three dimensions.
- Fault and Fold Networks: 3D representation of tectonic features to support structural analysis and hazard assessment.
- Resource Modeling Inputs: Conceptual models provide a framework for probabilistic mineral or hydrocarbon prospectivity mapping.

These models enhance understanding of subsurface conditions and support simulation, exploration planning, and geohazard analysis.

4.7 Mineral Potential and Geochemical Screening Layers

Integrated datasets are used to generate **mineral potential maps** and **geochemical screening products**, combining lithological, structural, and geochemical indicators:

- Prospectivity Mapping: Statistical and machine-learning–based models identify areas with high likelihood of mineralization.
- Geochemical Anomalies: Interpolation and spatial analysis of soil, rock, and stream sediment geochemistry reveal zones of interest.
- Uncertainty Visualization: Probability surfaces and confidence layers document areas with higher uncertainty or sparse data coverage.

These products support preliminary exploration, targeted field campaigns, and risk-informed planning.

4.8 Interactive Geovisualization Dashboards

To facilitate accessibility and usability, analytical outputs are coupled with **interactive geovisualization dashboards** hosted within the SUTGMM server environment:

- Dynamic Map Layers: Users can toggle lithological, structural, geophysical, and geochemical layers for customized analysis.
- Query and Filtering Tools: Attribute-based queries allow filtering by lithology, stratigraphy, or geophysical properties.
- 3D Visualization Interfaces: Subsurface models and terrain derivatives can be interactively explored, rotated, and cross-sectioned.
- Exportable Outputs: Dashboards enable extraction of maps, vector layers, and analytical reports for offline use or publication.

These tools promote evidence-based decision-making and enhance engagement among researchers, institutional stakeholders, and planners.

4.9 Metadata and Provenance Documentation

All analytical outputs are accompanied by **comprehensive metadata and provenance records**, detailing:

- Source datasets, acquisition dates, and processing steps;
- Analytical methods, algorithms, and parameters;
- Quality indicators, confidence levels, and limitations;
- Version history and update logs.

This ensures that all products are **transparent, reproducible, and auditable**, supporting long-term usability and enabling future extension of analyses.

4.10 Deliverable Summary

The final outputs of the project include:

- Unified thematic geological maps at multiple scales.
- 3D conceptual and subsurface geological models.
- Mineral potential and geochemical screening layers with uncertainty documentation.
- Interactive geovisualization dashboards with query, filtering, and 3D exploration capabilities.

- Standardized metadata and provenance records for all layers and products.

By delivering these integrated outputs, the project translates previously **trapped and fragmented geoscientific data** into high-value, actionable intelligence. The combination of thematic mapping, 3D modeling, resource assessment, and interactive visualization ensures that the Makran Zone is supported by a **modern, accessible, and reproducible geoscientific knowledge base**, aligned with the objectives of the SUTGMM Programme.

Chapter 5: Conclusions, Project Boundaries, Risk Governance, and Strategic Impact

5.1 Project Limitations, Exclusions, and Risk Management

While the project aims to unlock trapped geoscientific data and generate actionable outputs for the Makran Zone, several **limitations and exclusions** define the boundaries of the research. Identifying these constraints ensures methodological clarity, sets realistic expectations, and guides the development of appropriate **risk management strategies**.

5.1.1 Project Limitations

a. Reliance on Existing Data

The project exclusively utilizes pre-existing datasets, including geological maps, borehole logs, geophysical surveys, and remote sensing products. No new field-based data acquisition, drilling campaigns, or geophysical surveys are conducted. As a result:

- Data coverage may be spatially incomplete, particularly in remote or inaccessible regions of the Makran Zone.
- Certain lithological units, structural features, or mineral occurrences may remain underrepresented, leading to gaps in analytical outputs.

b. Pilot-Scale Implementation

The SUTGMM framework is deployed as a pilot-scale demonstration, rather than a national or enterprise-level platform. Therefore:

- Outputs are designed for research, decision-support, and proof-of-concept purposes, not for statutory regulatory use.
- Long-term hosting, full-scale IT infrastructure management, and national-scale integration are beyond the project scope.

c. Scale and Resolution Constraints

While multi-scale geological maps (1:250,000 and 1:100,000) are used, resolution limitations of legacy maps and coarse remote sensing products may restrict the precision of local analyses. Fine-scale structural or lithological heterogeneity may not be fully captured.

d. Methodological Scope

The project emphasizes lightweight analytical workflows, supervised classification, and conceptual modeling rather than resource-intensive quantitative modeling:

- Probabilistic mineral assessments are indicative rather than compliance-grade reserve estimates.
- Geohazard analyses are preliminary, supporting research and planning rather than engineering design.

5.2 Exclusions

The project explicitly excludes:

- Acquisition of new geoscience data through field surveys, drilling, or geophysical campaigns.
- Legal negotiations, contractual arrangements, or formal policy reforms related to data access.
- Production of definitive, regulatory-grade geological maps or reports for licensing or statutory purposes.
- Integration of proprietary, restricted, or confidential industrial datasets without explicit authorization.

- Full-scale platform development beyond pilot implementations, including long-term IT operations, cybersecurity management, or national infrastructure deployment.

By defining these exclusions, the project maintains a focused scope and ensures alignment with achievable objectives.

5.3 Risk Management Strategies

Several risks are associated with the pilot implementation of SUTGMM and the integration of heterogeneous datasets. The project incorporates proactive strategies to mitigate these risks:

a. Data Availability and Quality Risks

- Mitigation: Perform early-stage inventory and evaluation of datasets, document gaps, and prioritize high-value sources for integration. Include uncertainty layers to indicate low-confidence areas.
- b. Data Integration and Harmonization Challenges
- Mitigation: Implement standardized metadata schemas, controlled vocabularies, and automated preprocessing scripts to ensure spatial, thematic, and attribute consistency. Use iterative validation with field-verified points where available.

c. Computational and Infrastructure Risks

- Mitigation: Deploy workflows on centralized SUTGMM servers with scalable storage and processing capabilities. Implement version-controlled pipelines to allow rollback and reproducibility in case of errors.

d. Analytical and Interpretation Risks

- Mitigation: Employ iterative machine-learning workflows with expert review and cross-validation against georeferenced maps. Document assumptions, limitations, and uncertainty measures in all analytical outputs.

e. Ethical, Legal, and Access Risks

- Mitigation: Apply access controls, anonymization, and aggregation strategies for sensitive data. Comply with institutional, national, and international data governance standards.

5.4 Implications for Project Deliverables

By clearly articulating limitations, exclusions, and risk management strategies:

- Users of the SUTGMM outputs are informed of potential constraints in data coverage, resolution, and interpretive certainty.
- The project maintains methodological transparency, reproducibility, and ethical compliance.
- Pilot-scale implementation ensures that insights and workflows can be scaled, adapted, or extended in future research or institutional initiatives without compromising scientific integrity.

This section provides a **structured understanding of the project boundaries**, aligning stakeholder expectations and ensuring that the SUTGMM pilot demonstrates both the potential and the responsible use of unlocked geoscientific data in the Makran Zone.

5.5 Expected Outcomes and Impact

The SUTGMM pilot project in the Makran Zone is designed to deliver measurable outcomes that span scientific advancement, institutional capacity building, and socio-economic benefits. By systematically unlocking trapped geoscientific data and integrating heterogeneous datasets, the project transforms underutilized information into actionable geological knowledge.

5.5.1 Scientific Outcomes

a. Enhanced Geological Understanding

- Production of unified, multi-scale thematic geological maps provides a coherent representation of lithological units, stratigraphy, and structural features.
- Integration of geophysical, remote sensing, and borehole datasets enables refined 3D conceptual models, improving understanding of subsurface architecture and tectonic domains.
- Iteratively validated machine-learning classifications enhance interpretive accuracy and provide reproducible workflows for future studies.
- b. Methodological Contributions

- Development of standardized workflows for data curation, harmonization, integration, and analysis establishes transferable protocols applicable to other regions with fragmented geoscientific data.
- Metadata enrichment and provenance tracking promote reproducibility and transparency, supporting scientific rigor and cross-institutional collaboration.

5.5.2 Institutional and Capacity-Building Outcomes

a. Knowledge Activation and Data Governance

- Consolidation of legacy datasets under a standardized metadata and governance framework improves discoverability, accessibility, and usability of institutional geoscience data.
- Training materials, documented workflows, and interactive dashboards build institutional capacity for geoscientific analysis, enabling staff and researchers to leverage datasets effectively.

b. ICT and Analytical Infrastructure Enhancement

- Deployment of server-based SUTGMM infrastructure provides a scalable, reproducible environment for multi-source data integration and geospatial analysis.
- Standardized pipelines for feature extraction, machine-learning classification, and thematic mapping strengthen the technical capacity of participating organizations.

5.5.3 Socio-Economic and Practical Impacts

a. Evidence-Based Planning and Resource Assessment

- Unified geological and structural maps, 3D conceptual models, and mineral potential layers support regional planning, mineral exploration, and hazard assessment.
- Probabilistic resource assessments and geochemical screening provide preliminary guidance for sustainable resource development while minimizing environmental risk.

b. Decision-Support and Stakeholder Engagement

- Interactive geovisualization dashboards allow policymakers, planners, and researchers to explore multi-source datasets, query information, and generate reports for informed decision-making.
- Transparent documentation of data provenance and analytical assumptions facilitates responsible use of geoscientific information in socio-economic and environmental planning.

5.5.4 Long-Term and Transferable Benefits

a. Scalability and Adaptability

- The SUTGMM framework, while implemented as a pilot, establishes a methodology for scaling to other regions, geoscientific domains, and institutional contexts.
- Reusable workflows and metadata standards create a foundation for future integration of additional datasets or expansion into larger-scale Earth data platforms.

b. Contribution to Open Science and Knowledge Sharing

- Structured metadata, reproducible analytical pipelines, and transparent documentation promote alignment with open science principles, facilitating data sharing, peer review, and collaborative research.
- Demonstrates a model for unlocking latent value in legacy geoscience data, providing a template for similar initiatives in other regions with fragmented data.

5.6 Summary

Collectively, the expected outcomes of the SUTGMM pilot in the Makran Zone include:

- Scientifically robust geological products – unified thematic maps, 3D models, and mineral potential layers.
- Institutional capacity enhancements – workflows, dashboards, and standardized metadata enabling reproducible analyses.
- Socio-economic utility – evidence-based planning, hazard assessment, and resource exploration support.
- Transferable methodologies – scalable and adaptable protocols for other regions and geoscientific domains.

By delivering these outcomes, the project demonstrates that systematically **unlocking trapped geoscientific data** can generate high-value knowledge, support sustainable development, and strengthen institutional and scientific capacity in the Makran Zone.

5.7 Project Timeline and Implementation Plan

The SUTGMM pilot project for the Makran Zone is designed as a **one-year initiative**, structured into sequential and overlapping phases to ensure systematic data curation, integration, analysis, and product delivery. The timeline emphasizes iterative validation, reproducibility, and alignment with the project's primary and secondary objectives.

5.7.1 Phase 1: Project Initiation and Data Inventory (Month 1–2)

Objectives:

- Establish project governance, roles, and responsibilities.
- Conduct a comprehensive inventory of existing geoscientific datasets from governmental agencies, academic institutions, and publicly available sources.
- Key Activities:
- Identification of data custodians and stakeholders.
- Collection of metadata, access permissions, and licensing information.
- Preliminary assessment of dataset quality, completeness, and spatial coverage.
- Deliverables:
- Project governance plan.
- Comprehensive dataset inventory with metadata summary.
- Data access agreements or documentation of usage restrictions.

5.7.2 Phase 2: Data Preprocessing and Georeferencing (Month 2–4)

Objectives:

- Prepare heterogeneous datasets for integration into the SUTGMM infrastructure.
- Georeference legacy geological maps and align all spatial datasets to a common coordinate system.

Key Activities:

- Preprocessing of raster datasets (DEM, satellite imagery) including calibration, correction, and reprojection.
- Topological and attribute corrections for vector datasets (maps, fault lines, boreholes).
- Georeferencing of geological maps and validation against reference points.
- Deliverables:
- Georeferenced geological maps at multiple scales.
- Preprocessed remote sensing and geophysical datasets.
- Metadata-enriched, harmonized datasets ready for integration.

5.7.3 Phase 3: Data Harmonization and Feature Extraction (Month 4–6)

Objectives:

- Standardize datasets for cross-source interoperability.
- Derive geospatial and analytical features for machine-learning and thematic mapping.

Key Activities:

- Attribute harmonization using controlled vocabularies.
- Spatial alignment and resolution normalization of raster and vector layers.
- Extraction of spectral, textural, topographic, structural, and geochemical features.
- Deliverables:
- Harmonized and normalized datasets with standardized metadata.
- Feature matrices prepared for supervised classification and analysis.

5.7.4 Phase 4: Data Integration and Unified Framework Construction (Month 6–8)

Objectives:

- Build a centralized geospatial framework integrating all curated datasets.
- Ensure traceability, provenance, and reproducibility for all analytical layers.

- Key Activities:
- Integration of raster and vector datasets into the SUTGMM knowledge base.
- Cross-validation of structural, lithological, and geophysical layers.
- Documentation of processing workflows, version control, and data lineage.

Deliverables:

- Centralized SUTGMM geospatial framework for the Makran Zone.
- Provenance and metadata documentation for all integrated layers.

5.7.5 Phase 5: Thematic Mapping, Machine-Learning Classification, and Analytical Outputs (Month 8–10)

Objectives:

- Generate refined geological products and analytical outputs.
- Validate outputs against field observations and legacy data.
- Key Activities:
- Supervised machine-learning classification using georeferenced maps and extracted features.
- Iterative refinement of thematic layers based on validation feedback.
- Integration of structural, geochemical, and geophysical data into 3D conceptual models.

Deliverables:

- Unified thematic geological maps at multiple scales.
- 3D conceptual and subsurface models.
- Mineral potential and geochemical screening layers with uncertainty documentation.

5.7.6 Phase 6: Geovisualization and Decision-Support Tools (Month 10–11)

Objectives:

- Develop interactive tools to explore and analyze the integrated datasets.
- Key Activities:
- Construction of web-based dashboards and GIS interfaces for multi-layer visualization.
- Implementation of query, filtering, and 3D navigation capabilities.
- Integration of provenance and metadata for transparent, reproducible use.

Deliverables:

- Interactive geovisualization dashboards.
- Exportable thematic maps, layers, and reports.
- Documentation and user guides for analytical and visualization tools.

5.7.7 Phase 7: Reporting, Training, and Knowledge Transfer (Month 11–12)

Objectives:

- Consolidate project outputs and ensure knowledge transfer to stakeholders.
- Key Activities:
- Preparation of final project report summarizing methods, results, and recommendations.
- Training workshops for institutional staff and researchers on SUTGMM workflows, dashboards, and analytical tools.
- Archiving of all datasets, workflows, and metadata in the SUTGMM server environment for long-term accessibility.

Deliverables:

- Comprehensive project report.
- Training materials and workshop documentation.
- Finalized and archived SUTGMM datasets and tools.

Table 2: Summary Timeline Table

Phase	Duration	Key Deliverables
1. Project Initiation & Data Inventory	Month 1–2	Dataset inventory, governance plan, access documentation
2. Data Preprocessing & Georeferencing	Month 2–4	Georeferenced maps, preprocessed datasets
3. Data Harmonization & Feature Extraction	Month 4–6	Harmonized datasets, feature matrices
4. Data Integration & Framework Construction	Month 6–8	Centralized SUTGMM framework, provenance documentation
5. Thematic Mapping & Analytical Outputs	Month 8–10	Thematic maps, 3D models, mineral potential layers
6. Geovisualization & Decision-Support	Month 10–11	Interactive dashboards, query tools, exportable layers
7. Reporting, Training & Knowledge Transfer	Month 11–12	Final report, training workshops, archived datasets

This phased implementation plan ensures that **all project objectives are systematically achieved**, with clear milestones for data curation, integration, analysis, and dissemination. The timeline also supports iterative validation, risk mitigation, and reproducible workflows, aligning with the SUTGMM principles and providing a structured roadmap for the one-year pilot.

5.8 Conclusion

The SUTGMM pilot project for the Makran Zone demonstrates a systematic approach to transforming **trapped and underutilized geoscientific data** into high-value, actionable knowledge. By leveraging legacy geological maps, remote sensing products, geophysical surveys, and borehole data, the project establishes a **server-based, integrated framework** that supports reproducible workflows, multi-source analysis, and dynamic geovisualization.

Key Achievements

1. Data Activation and Integration:

- Legacy geological maps have been georeferenced, harmonized, and integrated with complementary datasets, overcoming spatial, thematic, and format fragmentation.
- Standardized metadata, provenance tracking, and structured data governance enhance discoverability, reproducibility, and transparency.

2. Analytical Outputs:

- Unified thematic geological maps at multiple scales, 3D conceptual models, mineral potential layers, and geochemical screening products provide a comprehensive understanding of the Makran Zone.

- Interactive dashboards and GIS-based tools enable dynamic exploration, query, and visualization of multi-source datasets.

3. Capacity Building and Methodological Advancement:

- Documented workflows, training materials, and pilot-scale infrastructure strengthen institutional capacity for geoscientific analysis.
- Scalable and transferable methodologies provide a framework for similar initiatives in other regions, demonstrating the potential of unlocking latent value in existing geoscience datasets.

Strategic Significance

The project aligns with broader objectives of **evidence-based resource management, hazard assessment, and sustainable development** by providing:

- Scientifically robust outputs for research and planning;
- Decision-support tools for policymakers and stakeholders;
- Protocols for ethical, reproducible, and transparent use of geoscientific data.

By demonstrating the operationalization of heterogeneous and underutilized data within a structured, server-based environment, the SUTGMM pilot establishes a **model for digital transformation in geoscience knowledge management**. The insights, workflows, and tools developed through this project not only enhance understanding of the Makran Zone but also create a foundation for future expansion, regional scaling, and cross-institutional collaboration.

Final Statement

In conclusion, the SUTGMM pilot illustrates that systematically **unlocking trapped geoscientific data** can generate significant scientific, institutional, and socio-economic value. The project provides a replicable framework for transforming fragmented legacy datasets into integrated, actionable geoscience knowledge, enabling informed decision-making, resource planning, and hazard assessment while advancing the digital transformation of geoscience research in the region.

References

Alinaghi, A., Koulakov, I., Thybo, H., 2007. Seismic tomographic imaging of P - and S -waves velocity perturbations in the upper mantle beneath Iran. Geophysical Journal International 169, 1089–1102. https://doi.org/10.1111/j.1365-246X.2007.03317.x

Alpaydin, E., 2020. Introduction to machine learning, 4th ed, Adaptive computation and machine learning series. The MIT Press, Cambridge, Massachusetts.

Alvarez, W., Engelder, T., Geiser, P.A., 1978. Classification of solution cleavage in pelagic limestones. Geology 6, 263. https://doi.org/10.1130/0091- 7613(1978)6<263: COSCIP>2.0.CO;2

Amani, M., Ghorbanian, A., Ahmadi, S.A., Kakooei, M., Moghimi, A., Mirmazloumi, S.M., Moghaddam, S.H.A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., Brisco, B., 2020. Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 13, 5326–5350. https://doi.org/10.1109/JSTARS.2020.3021052

Arthurton, R.S., Farah, A., Ahmed, W., 1982. The Late Cretaceous-Cenozoic history of western Baluchistan Pakistan—the northern margin of the Makran subduction complex. Geological Society, London, Special Publications 10, 373–385. https://doi.org/10.1144/GSL.SP.1982.010.01.25

Baatz, M., Schäpe, A., 2000. Multiresolution segmentation: An optimization approach for high quality multi-scale image segmentation. Presented at the Angewandte Geographische Informationsverarbeitung XII, pp. 12–23.

Back, S., Morley, C.K., 2016. Growth faults above shale – Seismic-scale outcrop analogues from the Makran foreland, SW Pakistan. Marine and Petroleum Geology 70, 144–162. https://doi.org/10.1016/j.marpetgeo.2015.11.008

Bahdanau, D., Cho, K., Bengio, Y., 2016. Neural Machine Translation by Jointly Learning to Align and Translate. https://doi.org/10.48550/arXiv.1409.0473

Berberian, F., Muir, I.D., Pankhurst, R.J., Berberian, M., 1982. Late Cretaceous and early Miocene Andean-type plutonic activity in northern Makran and Central Iran. Journal of the Geological Society 139, 605–614. https://doi.org/10.1144/gsjgs.139.5.0605

Bijwaard, H., Spakman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. Journal of Geophysical Research: Solid Earth 103, 30055–30078. https://doi.org/10.1029/98JB02467

Bird, P., Toksöz, M.N., Sleep, N.H., 1975. Thermal and mechanical models of continentcontinent convergence zones. J. Geophys. Res. 80, 4405–4416. https://doi.org/10.1029/JB080i032p04405

Blaschke, T., 2010. Object based image analysis for remote sensing. ISPRS Journal of Photogrammetry and Remote Sensing 65, 2–16. https://doi.org/10.1016/j.isprsjprs.2009.06.004

Blaschke, T., Hay, G.J., Kelly, M., Lang, S., Hofmann, P., Addink, E., Queiroz Feitosa, R., Van Der Meer, F., Van Der Werff, H., Van Coillie, F., Tiede, D., 2014. Geographic ObjectBased Image Analysis – Towards a new paradigm.

ISPRS Journal of Photogrammetry and Remote Sensing 87, 180–191. https://doi.org/10.1016/j.isprsjprs.2013.09.014

Breiman, L., 2001. Random Forests. Machine Learning 45, 5–32. https://doi.org/10.1023/A:1010933404324

Breiman, L., 1996. Bagging predictors. Machine Learning 24, 123–140. https://doi.org/10.1007/BF00058655

Burg, J., Bernoulli, D., Smit, J., Dolati, A., Bahroudi, A., 2008. A giant catastrophic mud-and- debris flow in the Miocene Makran. Terra Nova 20, 188–193. https://doi.org/10.1111/j.1365-3121.2008.00804.x

Burg, J.-P., 2018. Geology of the onshore Makran accretionary wedge: Synthesis and tectonic interpretation. Earth-Science Reviews 185, 1210–1231. https://doi.org/10.1016/j.earscirev.2018.09.011

Byrne, D.E., Sykes, L.R., Davis, D.M., 1992. Great thrust earthquakes and aseismic slip along the plate boundary of the Makran Subduction Zone. Journal of Geophysical Research: Solid Earth 97, 449–478. https://doi.org/10.1029/91JB02165

Chandra, U., 1984. Focal mechanism solutions for earthquakes in Iran. Physics of the Earth and Planetary Interiors 34, 9–16. https://doi.org/10.1016/0031-9201(84)90080-3

DeMets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. Geophysical Journal International 181, 1–80. https://doi.org/10.1111/j.1365-246X.2009.04491.x

Dercourt, J., Zonenshain, L.P., Ricou, L.-E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.-C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P., Biju-Duval, B., 1986. Geological evolution of the tethys belt from the atlantic to the pamirs since the LIAS. Tectonophysics 123, 241–315. https://doi.org/10.1016/0040- 1951(86)90199-X

Dimitrov, L.I., 2002. Mud volcanoes—the most important pathway for degassing deeply buried sediments. Earth-Science Reviews 59, 49–76. https://doi.org/10.1016/S0012-8252(02)00069-7

Dolati, A., 2010. Stratigraphy, structural geology and low-temperature thermochronology across the Makran accretionary wedge in Iran. ETH Zürich, Switzerland.

Drăguţ, L., Csillik, O., Eisank, C., Tiede, D., 2014. Automated parameterisation for multi-scale image segmentation on multiple layers. ISPRS Journal of Photogrammetry and Remote Sensing 88, 119–127. https://doi.org/10.1016/j.isprsjprs.2013.11.018

Ellouz-Zimmermann, N., Deville, E., Müller, C., Lallemant, S., Subhani, A.B., Tabreez, A.R., 2007. Impact of Sedimentation on Convergent Margin Tectonics: Example of the Makran Accretionary Prism (Pakistan), in: Lacombe, O., Roure, F., Lavé, J., Vergés, J. (Eds.), Thrust Belts and Foreland Basins, Frontiers in Earth Sciences. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 327–350. https://doi.org/10.1007/978-3-540- 69426-7_17

Engdahl, E.R., Jackson, J.A., Myers, S.C., Bergman, E.A., Priestley, K., 2006. Relocation and assessment of seismicity in the Iran region. Geophysical Journal International 167, 761–778. https://doi.org/10.1111/j.1365-246X.2006.03127.x

Falcon, N.L., 1974. Southern Iran: Zagros Mountains. Geological Society, London, Special Publications 4, 199–211. https://doi.org/10.1144/GSL.SP.2005.004.01.11

Farhoudi, G., Karig, D.E., 1977. Makran of Iran and Pakistan as an active arc system. Geology 5, 664. https://doi.org/10.1130/0091-7613(1977)5<664:MOIAPA>2.0.CO;2

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The Shuttle Radar Topography Mission. Rev. Geophys. 45, RG2004. https://doi.org/10.1029/2005RG000183

Fathian, A., 2022. Active tectonics of the Zagros front (PhD thesis). RWTH Aachen University, Aachen, Germany.

GEBCO Compilation Group, 2023. GEBCO 2023 Global Bathymetry and Topography. https://doi.org/10.5069/G9D21VTT

Gharibreza, M., 2016. Evolutionary trend of paleoshorelines in the Coastal Makran zone (southeast Iran) since the mid-Holocene. Quaternary International 392, 203–212. https://doi.org/10.1016/j.quaint.2015.06.030

Goetz, A.F.H., Rock, B.N., Rowan, L.C., 1983. Remote sensing for exploration; an overview. Economic Geology 78, 573–590. https://doi.org/10.2113/gsecongeo.78.4.573

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of

Environment 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Grando, G., McClay, K., 2007. Morphotectonics domains and structural styles in the Makran accretionary prism, offshore Iran. Sedimentary Geology 196, 157–179. https://doi.org/10.1016/j.sedgeo.2006.05.030

Hafkenscheid, E., Wortel, M.J.R., Spakman, W., 2006. Subduction history of the Tethyan region derived from seismic tomography and tectonic reconstructions. Journal of Geophysical Research: Solid Earth 111. https://doi.org/10.1029/2005JB003791

Haghipour, N., Burg, J.-P., 2014. Geomorphological analysis of the drainage system on the growing Makran accretionary wedge. Geomorphology 209, 111–132. https://doi.org/10.1016/j.geomorph.2013.11.030

Harms, J.C., Cappel, H.N., Francis, D.C., 1984. The Makran coast of Pakistan: its stratigraphy and hydrocarbon potential. Marine geology and oceanography of Arabian Sea and coastal Pakistan 3.

Hatzfeld, D., Molnar, P., 2010. Comparisons of the kinematics and deep structures of the Zagros and Himalaya and of the Iranian and Tibetan plateaus and geodynamic implications. Reviews of Geophysics 48, RG2005. https://doi.org/10.1029/2009RG000304

He, P., Wen, Y., Xu, C., Chen, Y., 2019. Complete three-dimensional near-field surface displacements from imaging geodesy techniques applied to the 2016 Kumamoto earthquake. Remote Sensing of Environment 232, 111321. https://doi.org/10.1016/j.rse.2019.111321

Heidarzadeh, M., Pirooz, M.D., Zaker, N.H., Yalciner, A.C., Mokhtari, M., Esmaeily, A., 2008. Historical tsunami in the Makran subduction zone off the southern coasts of Iran and Pakistan and results of numerical modeling. Ocean Engineering 35, 774–786. https://doi.org/10.1016/j.oceaneng.2008.01.017

Jackson, J., McKenzie, D., 1984. Active tectonics of the Alpine-Himalayan Belt between western Turkey and Pakistan. Geophysical Journal International 77, 185–264. https://doi.org/10.1111/j.1365-246X.1984.tb01931.x

Jacob, K.H., Quitmeyer, R., Farah, A., DeJong, K.A., 1979. The Makran region of Pakistan and Iran: trench-arc system with active plate subduction. Quittmeyer, Richard Charles 73.

Jensen, J.R., 2016. Introductory digital image processing: a remote sensing perspective, 4th ed, Pearson series in geographic information science. Pearson Education, Glenview, Ill.

Jordan, M.I., Mitchell, T.M., 2015. Machine learning: Trends, perspectives, and prospects. Science 349, 255–260. https://doi.org/10.1126/science.aaa8415

Kaveh-Firouz, A., Mohammadi, A., Görüm, T., Sarıkaya, M.A., Alizadeh, H., Akbaş, A., Mirarabi, A., 2023. Main drivers of drainage pattern development in onshore Makran Accretionary Wedge, SE Iran. International Journal of Earth Sciences 112, 539–559. https://doi.org/10.1007/s00531-022-02270-6

Kelleher, J.D., Tierney, B., 2018. Data science, The MIT Press essential knowledge series. The MIT Press, Cambridge, Massachusetts.

Kent, R.G., 1953. Old Persian: Grammar, Texts, Lexicon. American Oriental Society, New Haven.

Khan, M.A., Raza, H.A., Alam, S., 1991. Petroleum geology of the Makran region: implications for hydrocarbon occurrence in cool basins. Journal of Petroleum Geology 14, 5–18. https://doi.org/10.1111/j.1747-5457.1991.tb00295.x

Khorrami, F., Vernant, P., Masson, F., Nilfouroushan, F., Mousavi, Z., Nankali, H., Saadat, S.A., Walpersdorf, A., Hosseini, S., Tavakoli, P., Aghamohammadi, A., Alijanzade, M., 2019. An up-to-date crustal deformation map of Iran using integrated campaign-mode and permanent GPS velocities. Geophysical Journal International 217, 832–843. https://doi.org/10.1093/gji/ggz045

Kopf, A.J., 2002. SIGNIFICANCE OF MUD VOLCANISM. Reviews of Geophysics 40. https://doi.org/10.1029/2000RG000093

Kopp, C., Fruehn, J., Flueh, E.R., Reichert, C., Kukowski, N., Bialas, J., Klaeschen, D., 2000. Structure of the Makran subduction zone from wide-angle and reflection seismic data. Tectonophysics 329, 171–191. https://doi.org/10.1016/S0040-1951(00)00195-5

Krizhevsky, A., Sutskever, I., Hinton, G.E., 2017. ImageNet classification with deep convolutional neural networks. Commun. ACM 60, 84–90. https://doi.org/10.1145/3065386

Kukowski, N., Lallemand, S.E., Malavieille, J., Gutscher, M.-A., Reston, T.J., 2002. Mechanical decoupling and basal duplex formation observed in sandbox experiments with application to the Western Mediterranean Ridge accretionary complex. Marine Geology 186, 29–42. https://doi.org/10.1016/S0025-3227(02)00171-8

Lambeck, K., 1996. Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth and Planetary Science Letters 142, 43–57. https://doi.org/10.1016/0012-821X(96)00069-6

LeCun, Y., Bengio, Y., Hinton, G., 2015. Deep learning. Nature 521, 436–444. https://doi.org/10.1038/nature14539

LeCun, Y., Bottou, L., Bengio, Y., Haffner, P., 1998. Gradient-based learning applied to document recognition. Proceedings of the IEEE 86, 2278–2324. https://doi.org/10.1109/5.726791

Liaw, A., Wiener, M., 2002. Classification and regression by randomForest. R news 2/3.

Lillesand, T.M., Kiefer, R.W., Chipman, J.W., 2015. Remote sensing and image interpretation, 7th ed. John Wiley & Sons, Inc, Hoboken, N.J.

Lu, D., Weng, Q., 2007. A survey of image classification methods and techniques for improving classification performance. International Journal of Remote Sensing 28, 823–870. https://doi.org/10.1080/01431160600746456

Mayrhofer, M., 1978. Handbuch des Altpersischen. Wiesbaden: Harrassowitz.

McCall, G.J.H., 1985. Area report, East Iran Project-Area No: 1 (North Makran & South Baluchestan) (No. Report No.57). Geological Survey of Iran, Tehran.

McCall, G.J.H., 1983. Mélanges of the Makran, southeastern Iran. Hutchinson Ross Publishing Company, Ophiolitic and related mélanges 66, 292–299.

McCall, G.J.H., Kidd, R.G.W., 1982. The Makran, Southeastern Iran: the anatomy of a convergent plate margin active from Cretaceous to Present. Geological Society, London, Special Publications 10, 387–397. https://doi.org/10.1144/GSL.SP.1982.010.01.26

McClay, K.R., 1992. Thrust tectonics. Champan & Hall, London New York Tokyo [etc.].

Molnar, P., Stock, J.M., 2009. Slowing of India's convergence with Eurasia since 20 Ma and its implications for Tibetan mantle dynamics. Tectonics 28, 2008TC002271. https://doi.org/10.1029/2008TC002271

Nazari, H., 2024. The Server based unified thematic Geological mapping, Presented at the GEOKURDISTAN VI, 5-7 November 2024, Sulaimani, Kurdistan Region, Iraq.

Nazari, H., Karami, J., Arefipour, S., 2024a. SUTGM PROGRAMME: A New Protocol for ServerBased Unified Thematic Geological Mapping (GeoNexus), UCCGHA 027. UNESCO Chair on Coastal Geo-Hazards Analysis.

Nazari, H., Karami, J., Arefipour, S., 2024b. Geological Mapping in the Era of AI: Leveraging Innovation for Precision and Speed. Presented at the Mediterranean Geoscience Union (MedGU), 25-28 Nov. 2024, Barcelona, Spain.

Nazari, H., Karami, J., Arefipour, S., 2023a. The Server based unified thematic Geological mapping in cloud computing, approach: Deep Machin Learning. Presented at the Regional symposium on Geospatial Information Exchange and Research (GIER), 07-08 March, Muscat, Oman.

Nazari, H., Karami, J., Arefipour, S., 2022. The Server based unified thematic Geological mapping in cloud computing, presented at the AAPG Europe Regional Conference: Revitalizing Old Fields and Energy Transition in Mature Basins, 3-4 May 2022, Budapest, Hungary.

Nazari, H., Karami, J., Arefipour, S., Aghaali, E., 2023b. Using artificial intelligence and Machine learning in the mapping of quaternary units. Quaternary of Iran 8, 379–403.

Normand, R., 2019. Geomorphological, sedimentological and structural signals of deformation in a silent subduction zone: an investigation of the Makran (Iran). Université de Genève. https://doi.org/10.13097/ARCHIVE-OUVERTE/UNIGE:117482

Page, W.D., Alt, J.N., Cluff, L.S., Plafker, G., 1979. Evidence for the recurrence of largemagnitude earthquakes along the Makran coast of Iran and Pakistan. Tectonophysics 52, 533–547. https://doi.org/10.1016/0040-1951(79)90269-5

Paul, J., Bürgmann, R., Gaur, V.K., Bilham, R., Larson, K.M., Ananda, M.B., Jade, S., Mukal, M., Anupama, T.S., Satyal, G., Kumar, D., 2001. The motion and active deformation of India. Geophysical Research Letters 28, 647–650. https://doi.org/10.1029/2000GL011832

Platt, J.P., Leggett, J.K., Young, J., Raza, H., Alam, S., 1985. Large-scale sediment underplating in the Makran accretionary prism, southwest Pakistan. Geol 13, 507. https://doi.org/10.1130/0091-7613(1985)13<507:LSUITM>2.0.CO;2

Powell, C.McA., 1979. A morphological classification of rock cleavage. Tectonophysics 58, 21–34. https://doi.org/10.1016/0040-1951(79)90320-2

Quittmeyer, R.C., Kafka, A.L., Armbruster, J.G., 1984. Focal mechanisms and depths of earthquakes in central Pakistan: A tectonic interpretation. Journal of Geophysical Research: Solid Earth 89, 2459–2470. https://doi.org/10.1029/JB089iB04p02459

Richards, J.A., 2013. Remote Sensing Digital Image Analysis: An Introduction, 5th ed. Springer, Berlin.

Sabins, F.F.J., Ellis, J.M., 2020. Remote sensing: Principles, Interpretation, and Applications, 4th ed. Waveland Press, Inc, Long Grove (Illinois).

Schmidhuber, J., 2015. Deep learning in neural networks: An overview. Neural Networks 61, 85–117. https://doi.org/10.1016/j.neunet.2014.09.003

Schmitt, R., 1991. The Bisitun Inscriptions of Darius the Great: Old Persian Text, Corpus Inscriptionum Iranicarum I, 1, Texts I. London.

Shah-Hosseini, M., Ghanavati, E., Morhange, C., Naderi Beni, A., Lahijani, H.A., Hamzeh, M.A., 2018. The evolution of Chabahar beach ridge system in SE Iran in response to Holocene relative sea level changes. Geomorphology 318, 139–147. https://doi.org/10.1016/j.geomorph.2018.06.009

Simonyan, K., Zisserman, A., 2014. Very Deep Convolutional Networks for Large-Scale Image Recognition. https://doi.org/10.48550/ARXIV.1409.1556

Smith, G., McNeill, L., Henstock, T.J., Bull, J., 2012. The structure and fault activity of the Makran accretionary prism. Journal of Geophysical Research: Solid Earth 117. https://doi.org/10.1029/2012JB009312

Snead, R.J., 1993. Uplifted marine terraces along the Makran coast of Pakistan and Iran, in: Himalaya to the Sea. Routledge, London, pp. 327–362.

Stöcklin, J., 1968. Structural history and tectonics of Iran: a review. American Association of Petroleum Geologists Bulletin 52, 1229–1258.

Stoneley, R., 1974. Evolution of the Continental Margins Bounding a Former Southern Tethys. The Geology of Continental Margins.

Sutskever, I., Vinyals, O., Le, Q.V., 2014. Sequence to Sequence Learning with Neural Networks. https://doi.org/10.48550/ARXIV.1409.3215

Vernant, Ph., Nilforoushan, F., Hatzfeld, D., Abbassi, M.R., Vigny, C., Masson, F., Nankali, H., Martinod, J., Ashtiani, A., Bayer, R., Tavakoli, F., Chéry, J., 2004. Present-day crustal deformation and plate kinematics in the Middle East constrained by GPS measurements in Iran and northern Oman. Geophysical Journal International 157, 381–398. https://doi.org/10.1111/j.1365-246X.2004.02222.x

Vita-Finzi, C., 1987. 14 C deformation chronologies in coastal Iran, Greece and Jordan. JGS 144, 553–560. https://doi.org/10.1144/gsjgs.144.4.0553

Vita-Finzi, C., 1979. Contributions to the Quaternary geology of southern Iran. Geological and Mineral Survey of Iran 47, 30–47.

Von Rad, U., Berner, U., Delisle, G., Doose-Rolinski, H., Fechner, N., Linke, P., Lückge, A., Roeser, H.A., Schmaljohann, R., Wiedicke, M., Parties, S. 122/130 S., Block, M., Damm, V., Erbacher, J., Fritsch, J., Harazim, B., Poggenburg, J., Scheeder, G., Schreckenberger, B., Von Mirbach, N., Drews, M., Walter, S., Ali Khan, A., Inam, A., Tahir, M., Tabrez, A.R., Cheema, A.H., Pervaz, M., Ashraf, M., 2000. Gas and fluid venting at the Makran accretionary wedge off Pakistan. Geo-Marine Letters 20, 10–19. https://doi.org/10.1007/s003670000033

White, R.S., Klitgord, K., 1976. Sediment deformation and plate tectonics in the Gulf of Oman. Earth and Planetary Science Letters 32, 199–209. https://doi.org/10.1016/0012-821X(76)90059-5

White, R.S., Louden, K.E., 1982. The Makran continental margin: structure of a thickly sedimented convergent plate boundary: convergent margins: field investigations of margin structure and stratigraphy. AAPG, Studies in Continental Margin Geology 499– 518.

Zhou, Z.-H., 2012. Ensemble methods: foundations and algorithms, Online-Ausg. ed, Chapman & Hall. Taylor & Francis, Boca Raton, FL.