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REVIEW

Regional Mapping of Basement Lithologies Using Geospatial Data in Semi-Arid Regions: Techniques, Advancements and Applications

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ABSTRACT

Lithological mapping in semi-arid regions has witnessed a phase of transformation due to advancement in remote sensing technology. This has permitted a more comprehensive understanding of surface lithological units. This review explores the evolution of remote sensing mapping techniques and their diverse uses at semi-arid regions, underscoring the significance of the mapping procedure and the prospects. Remote sensing technology has been advancing with moderate to high resolution spaceborne and airborne sensors, unmanned aerial vehicle (UAV) technology and LiDAR (light detection and ranging). These have significantly enhanced capacity, accuracy and the scope of lithological mapping procedures. Especially, the advancement of machine learning and Artificial Intelligent (AI) in automated remote sensing data analysis has ignited more precise ways of identifying and classification of lithological units. Using hybrid remote sensing/machine learning mapping techniques has extended the horizon of geological studies where mineral exploration, water resource management, land use planning, environmental assessments, and risk mitigation are particularly considered. The maps derived provide deeper insights into accurate delineation of mineral deposits, identification of potential sources of water, and aiding those making informed decision making for land development and resource management. The importance of hybrid remote sensing/ machine learning techniques lies with the profound contributions made through geological history, resource exploration, environmental preservation, and risk management directed to fragile ecosystems such as semi-arid environments. The future of the hybrid methodologies holds promise for further advancements in integrating various data sources, exploitation of their contextual properties, refining AI algorithms for faster and more accurate analysis, and methodologies that are specific to environments. These evolving technologies and diverse applications present a trajectory targeted at more comprehensive utilization of geological resources and improvement of environmental stewardship even to fragile regions.

Keywords: Remote Sensing imagery; Lithological mapping; Artificial Intelligent (AI) techniques; Geophysical surveys; Data integration

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1. Introduction

Lithological background is fundamentally an essential part of the Earth's crust and have numerous benefits to humanity [1]. The basement lithologies are foundation and yet enigmatic for understanding geology. They provide building materials [2], host valuable mineral and energy resources, shape the Earth's surface and geological processes, store and distribute water resources, and serve as subjects of scientific study for understanding geological hazards [3–6]. The utilization and management of lithologies and their resources contribute to economic development, technological advancement, environmental sustainability, and our overall quality of life [7]. Basement lithologies are a type of geological formations that describes the layers of rock that underlie the earth's surface and are differentiated as igneous, sedimentary, or metamorphic rocks [8]. They usually contain the soils and other geological materials existing on the earth's surface and underneath. In some regions, the basement lithologies may not be directly visible yet, revealing the shape of the topography with several benefits to human existence. They form the structural stability and solid foundation of the earth's surface and make the framework upon which every continent exists [9]. It is from them that support is provided for construction of every kind of infrastructure for human comfort. The natural resources are associated with basement rocks such as the valuable mineral deposits (gold, silver, copper, iron, Lithium etc.) and many other industrial minerals [10]. When these are exploited, they become materials for manufacturing, energy source and for economic development. Basement lithologies are the underground formations for storing water aquifers, and transmission of water through fractures and pore spaces [11]. These are tapped through drilling wells for drinking, irrigation and for industrial usage. Geothermal energy is derived from heat generated from hot earth crust rocks that come from the basement rocks [12], so that holes are drilled through the rocks to capture the heat, generate clean and sustainable energy, domestic electricity, and other industrial uses. It is also from basement rock that history of geology is derived [13]. The evidence is extracted of past tectonic events, volcanic activities, and metamorphism that enable research into historical formations. These might have taken a long time of alteration but, they reveal how evolution has been taking place all along. Natural environments of recreation and landscapes are linked to basement rocks and outcrops that form due to changing times, forming attractive places of tourism and rock climbing, hiking, and geological exploration areas [14]. They are the regions of natural habitats and biodiversity. Therefore, studying the distribution of basement and other rock outcrops provide to researcher's valuable geological insights into history, conservation, resource exploration, ground water systems, geothermal energy sources, and management of natural hazards.

1.1 Understanding Basement lithologies mapping development

Knowledge about lithologies has continued to evolve significantly over time, and it is driven by advancement in research which eventually has created deeper understanding, technology, and exploration techniques. The development of basement lithologies mapping indicates early geological observations between the 17th – 18th centuries. Older crystalline rocks beneath the sedimentary were discovered vastly to underly the foundations of nature. The 19th cc was the beginning of geological surveys such as the United States Geological Surveys (USGS), the British Geological Surveys (BGS) etc. The 19th – 20th cc was the emergence of geological theories where plate tectonics, continental drift, mountain building processes and earth crust were recognized. The 20th – 21st cc brought about the introduction of geophysical surveying techniques, remote sensing and GIS, advances in borehole drilling and seismic imaging, integration of multi-disciplinary data and 3D modelling, machine learning, and big data analytics. These have erupted the exploration of natural resources at both surface and the sub-surface [15–18]. A summary of these is presented in **Table 1**.

Table 1. Overview of basement lithological mapping.

Period	Methodology	Strength,	Limitations	Future Directions
Early Geological Observations (17th–18th Centuries)	Surface outcrops and field observations	Basic identification of basement rocks	Limited to surface exposures; no subsurface data	Building on early observations, integration with modern methods.
Rise of Geological Surveys (19th cc)	Hand-drawn geological maps	Systematic mapping; regional concepts	Limited spatial accuracy; no subsurface data	Digitization of historical maps and integration with modern data
Emergence of geological theory (late 19th-early 20th cc)	Theoretical frameworks for plate tectonics	Understanding of geological context	Doesn't provide detailed mapping data	Integration with advanced mapping techniques
Introduction of geophysical techniques (20th cc)	Seismic surveys, gravity, and magnetic measurements	Subsurface data; mapping in areas with limited outcrops	Costly and time-consuming; interpretation challenges	Integration with newer geophysical technologies
Development of Remote sensing and GIS (late 20th cc)	Satellite imagery, aerial photography, GIS	Visualization and integration of surface data	Limited surface features; need for ground truthing	Enhanced use of high-resolution satellite data and remote sensing techniques.
Advances in Borehole Drilling and Seismic imaging (late 20th-21cc)	Core drilling, Seismic imaging	Direct access to basement rocks; high resolution subsurface data	Limited coverage; expensive and complex	Expanding drilling and Seismic surveys in unexplored regions.
Integration of multi-disciplinary Data (21st cc)	Geological, geophysical, and geochemical data integration	Comprehensive modelling; improved accuracy	Data integration challenges; computational requirements	Further development of data analytics and machine learning
Exploration for natural resources	Resource exploration and hazard assessment	Economic benefits; risk mitigation	Focused on specific objectives; limited academic research	Sustainable resource management; advanced geohazard prediction

1.2 The significance of mapping basement lithologies

Basement rocks though both intrusive and extrusive form the deep foundation for resource reserves [19], where metallic ores are identified [20], including the regions of hydrocarbons deposits [21], and groundwater. Despite that all these are hidden beneath the earth's surface, they have always been of great importance to humanity [22], for hosting all our valuable natural mineral resources, source of boost to economy and where most essential infrastructural materials to the industry come from [23]. Basement rocks reliably are the base to ground water acquirers and subsequently the resource for irrigation agriculture, industries, and human populations general use. Certain categories of basement rocks are foundations for geothermal energy derivation and basis for information about geological history and processes [24]. Insights into plate tectonics, formation of continents and the earth's crust generally come from them. Knowledge of these deposits makes researchers able to characterize rock distribution, identify potentials for natural hazards such as earthquakes, landslides, and volcanic eruptions.

1.3 General Mapping Techniques for basement lithologies

Mapping lithologies accurately has a lot of benefits, to humanity, sustainability, and the environment [25]. There have been evolving methodologies for mapping basement rocks, each with its own advantages and limitations. The choice of which to use solely depends on specific geologic context, goal, and available resources. Nevertheless, the major mapping techniques are identified in **Table 2**.

Several techniques exist that have been applied in mapping basement rocks, some of these are now applied in combination, so that each leverages the

Table 2. Methods of mapping basement lithologies.

Method	Historical Development	Models/ Techniques	Strengths	Limitations	Future Directions
Geological mapping	Long standing tradition	Field observations	Detailed lithological information extraction	Limited in in-depth penetration	Integrating with remote sensing, geophysical and comprehensive understanding of the subsurface
Geophysical surveys	Early use of gravity techniques	Seismic, gravity, magnetic, electrical resistivity	Depth and subsurface structure visualization	Cost and equipment requirements, interpretation challenges	Advancement in imaging and data interpretation techniques, increased resolution.
Borehole Data	Drilling technologies have evolved	Core Sampling, downhole geophysics	Direct access to basement rocks, depth profiling	Limited spatial coverage, expensive and time consuming	Increased use of downhole geophysics and improved core analysis technique
Remote sensing	Aerial Photography to satellite imagery	Hyperspectral multispectral, LiDAR	Surface feature identification and landform analysis	Limited depth information, dependence on favourable surface condition	Advances in remote sensing technology, combining data from multiple sensors
Petrological & geochemical Analysis	Development of laboratory techniques	Thin section analysis, XRF, ICP-MS	Detailed mineral composition and geochemical data	Requires sample collection and analysis, limited to surface exposures	Improved analytical methods, non-destructive in situ techniques
Radiometric Dating	Discovery of radioactive decay	Radiocarbon, uranium-lead, potassium-argon dating	Absolute age determination	Limited to specific types of basement rocks, sample availability	Application of dating methods to more diverse basement rock types.

shortfalls of the other. However, the selection of what technique to apply depends solely on the scale of the study, resources available, how assessable is the region of study and the characteristics of the basement rocks. The common techniques are shown in **Figure 1**.

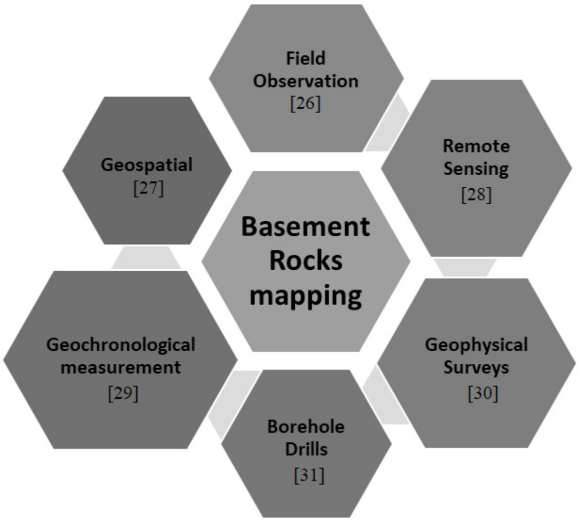

Figure 1. Basement rocks mapping techniques.

2. Challenges in basement lithology mapping

The processes of mapping basement lithologies can be challenging [32] as illustrated in **Figure 2**.

Undertaking general geologic mapping of basement rocks is deeper than lithological mapping. The general involves a comprehensive study of the Earths' surface, and encompasses every aspect of the structures, topography, and other geological features. The purpose is for creation of overall characteristics of the area of study [33]. In the other hand, lithological mapping specifically focuses on bringing out the rock classification, particularly identifying the lithology, mineral composition, and their physical characteristics. Focusing on the semi-arid environments, the general geological mapping provides a holistic view of the objects of the area such as the fault lines, fold structures, erosion patterns, and the landscape generally. Here, general geology provides broader understanding of the history and processes of formation that shaped the region. While the lithological mapping delves directly to the specific rock category highlighting the composition, distribution, the minerals present, their texture, and variations. This provides clue for resources exploitation [34].

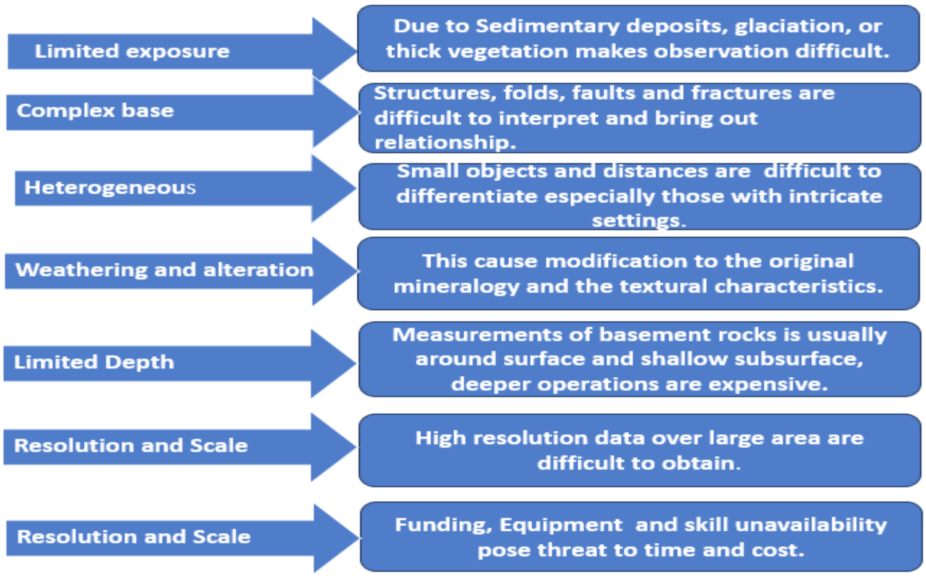

Figure 2. Challenges faced while mapping basement rocks.

Mapping basement rocks with lithological mapping techniques overcome the issues of limited surface exposures and applies geophysical methods such as seismic surveys, borehole logging, and satellite remote sensing to infer the subsurface geology of area of interest where compensation is provided at the long run [35]. Basement rocks also exhibit complex structures with lithological variations that impedes characterization of the rocks however, the use of advanced techniques such as 3D modeling, seismic tomography, and the integration of several data sources in a single operation provide solution to the complexity. Mineral resources are usually hidden in the basement rocks but with lithological mapping, these different categories of mineral types are identified using their spectral signatures and associated clues such as the structures that relate with mineral types. The existence of basement rocks influences groundwater flow and make it difficult to characterize, serving as a challenge to water resources assessment. To overcome this, lithological mapping provides insight into the water aquifer properties, fracture networks, and subtle variations information which become crucial for assessment [36]. There are other challenges faced with engineering construction as well as natural hazard assessment with unpredictable nature of basement rocks so that lithological information helps to solve, by providing information of fault zones, unstable rock formations, potential areas that are prone to seismic activity. These contributes a lot to assessment and mitigation of strategies for hazard assessment [37]. **Figure 3** illustrates the benefits of lithological mapping for basement rocks.

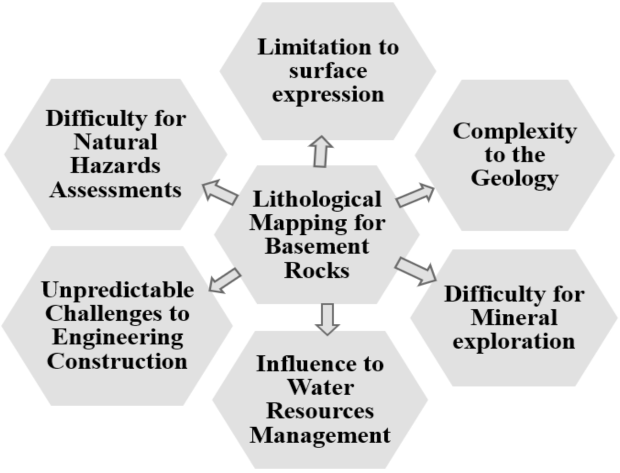

Figure 3. Lithological mapping overcoming basement rock challenges.

3. Lithological mapping techniques for semi-arid regions

It is noted that semi-arid regions have limited surface exposure due to weathering, harsh climatic conditions, or vegetation cover, a combination of ground-based and remote sensing methods becomes the most valuable, accurate and effective procedure to carry out mapping in these regions [38]. However, the aim of the study creates adjustment to the specific technique that best tackles the peculiar conditions such that contends with limited water, potential surface alterations because of the aridity and sparse vegetative condition of the area of interest. **Table 3** illustrates the different techniques that best suit semi-arid regions.

Table 3. Lithological Mapping Techniques in semi-arid regions.

S/N	Technique	Best Models	Strengths	Limitations	Future Directions
1	Remote Sensing	Hyperspectral imaging systems with Spectral Angle Mapper (SAM) and Spectral Feature Fitting (SFF) Techniques	Performs rapid coverage of large areas and detects surface mineralogy	There are issues of limited resolution for detailed mapping, weather effects and vegetation interferences	Advancements in Hyperspectral and high-resolution imaging coupled with integration of AI to the techniques will enhance data analysis.
2	Geophysical Surveys	Ground penetrating Radar (GPR), Seismic Reflection surveys, and Electrical Resistivity Tomography (ERT)	Reveals the subsurface variations, provides data on physical properties	Costs, logistics and interpretation challenges	Development of more cost effective and portable equipment to create improvement in interpretation techniques.
3	Drone Technology	LiDAR equipped drones and Multispectral imaging drones	High resolution imagery and topographic data. Access to hard-to-reach areas	Limited flight time and payload capacity are subject to weather dependency	Enhancements in flight endurance and payload capacity with improved sensor technology for varied terrain.
4	GIS	ArcGIS, QGIS, ENVI	Capacity for integration of multiple data sources. Mapping creation and analysis capabilities	Reliance on quality and availability of input data. There is Initial set-up and learning curve	Improved data interoperability and standardization. Real-time data integration for dynamic mapping
5	Field sampling and surveys	Systematic field surveys and sampling methodologies. Laboratory analysis techniques	Ground Truthing and verification of remote sensing data. Detailed analysis through sample collection	Labour-Intensive and time-consumption. Subject to sampling bias	Automation of sample analysis. Improved methodologies to reduce bias
6	Hybrid Approaches	Integration of various models and datasets for comprehensive mapping	Comprehensive data integration for accurate mapping	Complexity in managing multiple data sources	Development of more efficient data integration methods. Enhanced modelling and analysis techniques

The lithological mapping procedure particularly is one of the many methods mentioned earlier for studying basement rocks. It has to do with systematic identification of the rock types and how they are distributed around a particular environment [39]. The method exposes the researchers to understanding composition, distribution, and the relationship existing between them. Basement rocks are the oldest and typically concealed beneath younger sedimentary and volcanic cover rocks therefore, Lithological studies of them enable the determination of the structural arrangement of these rocks, history, and derive clues on how to do mineral exploration [40]. Additionally, it is useful for engineering construction, infrastructure, dams, tunnels, and bridges. These take place after adequate information are derived, especially the properties of the rocks which reveal regions of weakness, strengths, permeability, and stability for engineering works. These help construction engineers to determine the suitability of foundations, designs, and potential geological hazard environments [41]. Lithological mapping methods are many, and in recent times, researchers combine multiple techniques to create comprehensive knowledge and accuracy of outputs. AI and machine learning operations have been incorporated into the systems to enhance operability. These techniques have triggered improved technology, and the development of new remote sensing platforms that include drones, autonomous vehicles, and several other equipment in remote capabilities. **Table 4** identifies brief but in depth on the different methods of lithological mapping techniques for basement rocks.

It is worthy of mention also that basement rock studies carried out with the aid of lithological mapping serve as a key tool for environmental management. Several application areas are responsible resource utilization mapping, risk assessment, environmental protection, decision making and sustainable development. **Figure 4** identifies that several other potential areas of application of lithological maps are still under discovery, however, the prominent ones are indicated.

Table 4. Basement rock mapping and future directions.

Method	Models	Advantages	Demerits	Future Directions
Geological mapping	Classical field geology	Ground Truthed observations and use of context	Labour intensive and subject to interpreter biases	Integrated with remote sensing technologies for enhanced data visualization and 3D modelling.
Remote sensing	Satellite Imagery, Airborne geophysics, LiDAR	Wide area coverage, identification of lithological differences, and Detection of structural elements/ features	Limited to surface information with limited penetration for basement rocks, limited resolution for fine lithologies	Hyperspectral and multispectral data analysis with improved spatial and spectral resolution. Machine learning automation for feature detection
Geophysical surveys	Gravity measurements and Magnetic surveys	Detection of densities variation in sub-surface and magnetic anomalies	Limited to density differences that is easily affected by cultural noise and topography	Advanced inversion techniques for improved models, integrated with other geophysical data sources.
Borehole Logging	Core Samples and Downhole geophysics	Direct lithological information mapping, producing detailed sub-surface characterization	Limited to drilled borehole samples that makes the technique costly and time consuming	Advanced Sensor technology for real-time logging, integrated with drilling technology and sensors
Seismic Reflections	Reflection profiles and Refraction surveys	Depth and layer information, which leads to delineation of sub-surface interfaces	Limited resolution in highly faulted areas, and requires seismic sources with their equipment	Improved imaging through advanced processing, and integration with other geophysical data sources
Petrological Analysis	Thin section Analysis, and Geochemical analysis	Produces detailed mineralogical composition, identifies trace elements and isotopic ratios	Limited to samples from borehole drills, and there could be sample contamination accompanied with processing errors	Development of portable, in-situ analysis tools, with automation and miniaturization of lab equipment.
Machine Learning and Artificial intelligence (AI)	Various models and data	Has brought about automation and data driven insights	Requires high quality training data to be functional	Enhanced predictive modelling and data integration.

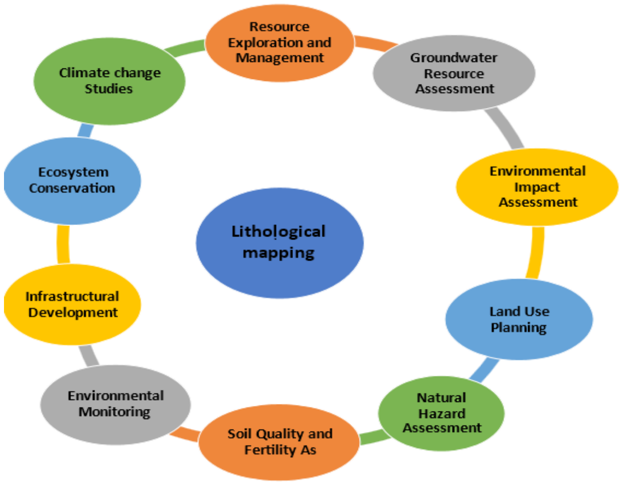

Figure 4. Areas of application for lithological mapping.

3.1 Remote sensing approaches to basement lithological mapping

Satellite remote sensing has dominated regional mapping studies over other methods, where the sensors and instruments used are mounted in orbiting platforms. The data received are used for detection, measurement, and analysis considering the principles behind electromagnetic radiation which reveals how the data is either reflected or emitted by the Earth's surface features [42]. The techniques have found vast use in monitoring and the environment [43]. The interaction of electromagnetic radiation with the Earth's surface and atmosphere is the key wavelengths. Sensors on board satellites capture radiation across different wavelengths, running through visible, infrared, and microwave regions of the electromagnetic spectrum. The collected data is then transmitted to ground stations, where they are processed, analyzed, and converted into meaningful information [44]. Apart from large-scale coverage, synoptic views, monitoring, climate patterns, land cover changes, and natural disasters are all discriminated [45]. There are repeated, regular, monitoring of dynamic processes and changes over time [46]. Tracking seasonal variations, land use dynamics, and long-term environmental trends. More so, analysis of various surface properties, such as vegetation health, land surface temperature, water quality, and geological features [47]. Three basic classes of remote sensing application are illustrated in **Figure 5**.

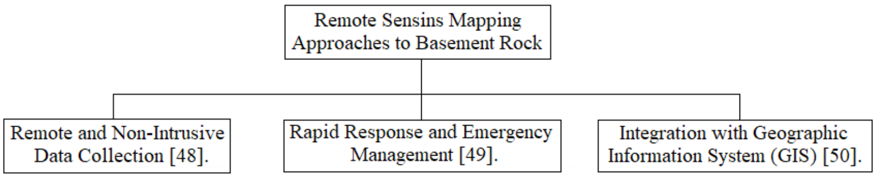

Figure 5. Remote sensing approaches to basement lithology mapping.

Images acquired with remote sensing platforms provide a broad overview of advantageous applications for large areas, and regions that have limited accessibility [51]. The electromagnetic wavelengths, ranging between visible, infrared, and microwave suffices and have been used to map a variety of surface features [52]. Amidst the several techniques available information about lithological variations, structural patterns and the underlying basement rocks are derived. The lithological units are distinct and are able to reveal spectral signatures, surface characteristics, through image interpretation techniques [53]. Additionally, structures with their sub-units such as lineaments, faults, fractures, folds, and other structural features are all discriminable [54]. Processes like determination of the orientation, alignment, and patterns of these structures, produce deeper visions into tectonic history and clear structural framework of the basement rocks. Data obtained from remote sensing has also found application vast array of applications, with relation to basement rocks including landforms and geomorphological studies. Rock types and some distinct surface expressions like erosion patterns, are all observed and analyzed from the imagery. Mountains, valleys, ridges, and river systems are part of details that provide clues about the underlying basement rock systems, mineral deposits, and their geological history.

Similarly, monitor and assess environmental impacts, such as deforestation, land degradation, and changes in land cover and land use patterns. The synoptic views provided at regional scale easily reveal the environmental changes with capacity for identifying areas where geological processes associated with basement rocks may have ecological consequences [55–57]. In retrospect, satellite image-based techniques enhance the mapping of basement rocks by providing valuable data on surface features, lithological variations, structural patterns, landforms, mineralization, and environmental changes. These techniques offer a cost-effective and efficient means of acquiring information over large areas, complementing traditional field-based mapping methods, and enabling a more comprehensive understanding of basement rock distributions and their geological characteristics.

The use of airborne image-based techniques has also played a substantial task with enhancement for the mapping of basement rocks [58]. Detailed and high-resolution data of the Earth's surface, by airborne techniques, where aerial photographs LiDAR (Light Detection and Ranging), and laser scanning technique have offered high-resolution imaging capabilities [59]. These techniques provide detailed and accurate imagery of the Earth's surface, allowing for the identification and mapping of subtle geological features associated with basement rocks [60]. Fine-scale surface expressions, textures, and structures can be observed and analyzed, providing valuable information for geological mapping. Airborne sensors can capture imagery in a broader spectral range compared to satellite sensors. This wider range of spectral bands allows for the detection of more specific spectral signatures related to different rock types and mineral assemblages. By analyzing the multispectral or hyperspectral data acquired through airborne techniques, geologists can differentiate lithological units, identify mineralogical variations, and map the distribution of different basement rock types [61].

Airborne image-based techniques provide higher spatial resolution compared to satellite-based techniques. This means that smaller geological features, such as rock outcrops, fractures, and fault zones, can be resolved and mapped in greater detail [62]. The increased spatial resolution enables geologists to identify and map geological structures associated with basement rocks more accurately, enhancing the understanding of their spatial distribution and relationships. Airborne image-based techniques offer flexibility and customization options [63]. Aerial surveys can be tailored to specific study areas or target regions, allowing for detailed coverage of areas of interest. This flexibility enables geologists to focus on specific geological targets or challenging terrains, providing a more comprehensive understanding of basement rock characteristics in those areas. Aerial surveys can also be repeated at different times, capturing temporal variations and monitoring changes related to basement rocks [64]. Airborne LiDAR technology provides precise and high-resolution topographic data. By measuring the time, it takes for laser pulses to return from the Earth's surface, LiDAR can create highly accurate digital elevation models (DEMs) and terrain models. These models aid in the identification of landforms, slope analysis, and the delineation of geological features related to basement rocks. LiDAR data, combined with aerial imagery, enhances the interpretation and mapping of geological structures and landforms [65].

Airborne image-based techniques can be integrated with other data sources, such as ground-based geophysical surveys, borehole data, and satellite imagery. This integration allows for the fusion of multiple datasets and enhances the accuracy and reliability of basement rock mapping. Airborne image-based techniques contain several attributes, they have high-resolution imaging capabilities, enhanced spectral range, improved spatial resolution, flexibility, and integration potential, which greatly enhances the mapping of basement rocks. These techniques provide detailed surface information, aid in the identification of geological structures and lithological variations and contribute to a comprehensive understanding of basement rock distributions and their geological characteristics. While laser scanning techniques contribute significantly to basement rock mapping, they also provide high-resolution topographic data, identify geological structures, maps rock exposures and outcrops, generating 3D models, aiding subsurface characterization, and facilitating integration with other data sources. These techniques enhance our understanding of the surface and subsurface characteristics of basement rocks, helping geologists in geological mapping, structural analysis, and geological interpretation [66–69].

Hyperspectral images and unmanned aerial vehicles (UAVs) techniques offer significant advancements in mapping basement rocks by providing detailed and precise data [70]. Hyperspectral imaging involves capturing images in numerous narrow and contiguous spectral bands, allowing for detailed analysis of the electromagnetic spectrum. Hyperspectral images provide highly resolved spectral information, enabling the identification and mapping of specific mineralogical and lithological variations associated with basement rocks [71]. The fine spectral resolution aids in distinguishing subtle differences in mineral composition and facilitates the identification of rock types and alteration zones that may be indicative of mineral deposits. Hyperspectral images offer the capability to identify and map minerals and mineral assemblages based on their unique spectral signatures. Each minerals exhibit characteristic absorption and reflectance patterns in different wavelengths. By analyzing hyperspectral data, geologists can identify specific minerals within the basement rocks, even when they are not visible to the naked eye. This information is crucial for understanding the mineral potential and resource assessment of basement rocks [72,73].

Hyperspectral images can provide valuable insights into subsurface features and structures associated with basement rocks. Certain wavelengths penetrate the Earth's surface to varying depths, allowing for the detection of buried features such as geological structures, fault zones, and buried mineralization [74]. By analyzing the spectral responses at different wavelengths, geologists can infer subsurface geological characteristics and gain a better understanding of the hidden features related to basement rocks. Unmanned aerial vehicles, commonly known as UAVs or drones, equipped with remote sensing instruments, provide a flexible and cost-effective means of acquiring high-resolution data. UAV-based remote sensing allows for targeted and localized surveys, providing detailed and precise images of specific areas of interest. These images can capture fine-scale surface features, geological structures, and lithological variations associated with basement rocks, facilitating accurate mapping and analysis. UAV-based techniques offer enhanced spatial resolution compared to satellite-based techniques. With UAVs, it is possible to acquire imagery at very high resolutions, capturing fine details of the Earth's surface [75]. This increased spatial resolution enables the identification and mapping of smaller-scale geological features, such as rock outcrops, fractures, and microstructures, which are critical in understanding the geological characteristics of basement rocks.

UAVs provide flexibility and accessibility, particularly in challenging terrains or areas with limited accessibility. They can access remote or rugged locations that may be difficult to reach by ground-based surveys. UAV-based techniques enable geologists to obtain data from specific areas of interest, such as cliffs, gorges, or steep slopes, enhancing the coverage and accuracy of basement rock mapping in these regions. UAV-based techniques allow for rapid data acquisition and real-time monitoring. With the ability to quickly deploy UAVs, geologists can acquire data efficiently and conduct repeated surveys over time, capturing temporal variations related to basement rocks. This capability is particularly valuable for monitoring geological processes, such as erosion, landslides, or volcanic activity, and assessing changes in the surface expression of basement rocks [76]. Hyperspectral images and UAV-based techniques offer significant enhancements in mapping basement rocks. The detailed spectral information from hyperspectral images aids in mineral identification, subsurface imaging, and lithological mapping. Meanwhile, UAV-based techniques provide enhanced spatial resolution, flexibility, and accessibility, enabling targeted surveys, detailed surface mapping, and real-time monitoring. These techniques contribute to a comprehensive understanding of basement rock characteristics, mineral potential, and geological processes.

3.2 Geophysical survey techniques for basement lithological mapping

Geophysical mapping techniques play a crucial role in enhancing the mapping of basement lithologies by providing valuable insights into subsurface geology [77]. Geophysical techniques, such as seismic reflection, ground-penetrating radar (GPR), and electrical resistivity tomography (ERT), provide imaging capabilities to penetrate the subsurface and visualize the geological structures associated with basement rocks [78]. These techniques allow for the identification and mapping of faults, fractures, folds, and other structural features that are indicative of the underlying basement geology. Geophysical methods help in delineating lithological boundaries and variations within the subsurface. Different rock types have distinct physical properties, such as density, magnetic susceptibility, and electrical conductivity [79,80]. Geophysical surveys, such as gravity, magnetic, and electromagnetic methods, can detect and map variations in these properties, aiding in identifying lithological units and their spatial distribution [81]. Geophysical techniques are valuable in identifying alteration zones and potential mineralization associated with basement rocks. Certain mineral deposits, such as hydrothermal systems, can induce changes in the physical properties of the rocks [82]. Geophysical surveys can detect anomalies in magnetic, electrical, or electromagnetic responses that are often associated with mineralization or alteration zones, providing indications of potential mineral deposits within the basement rocks [83].

Geophysical methods help in estimating the depth to basement rocks. By analyzing the response of different geophysical signals, such as seismic waves, electrical resistivity, or magnetic anomalies, geophysicists can estimate the depth of the basement interface [84]. This information is crucial for understanding the subsurface architecture and geometry of basement rocks and aids in accurate mapping. Geophysical techniques provide information about the physical properties of subsurface materials [85]. These properties, such as density, porosity, and elastic properties, influence the propagation of geophysical signals. By analyzing the responses of different geophysical methods, geologists can infer the physical properties of the basement rocks and gain insights into their lithology, strength, and deformation history. Geophysical mapping techniques can be integrated with other data sources, such as geological mapping, geochemical analysis, and remote sensing data [86]. This integration allows for a comprehensive understanding of basement rock characteristics and enhances the accuracy of mapping. By combining multiple datasets, geologists can refine interpretations, identify correlations between different data types, and create more detailed and reliable basement rock maps.

Geophysical techniques assist in targeting exploration efforts for mineral resources associated with basement rocks. By mapping geological structures, alteration zones, and potential mineralization, geophysical surveys help in prioritizing areas with high mineral potential, reducing exploration costs, and increasing the chances of successful mineral discoveries [87]. Geophysical mapping techniques provide valuable insights into the subsurface geology and enhance the mapping of basement rocks. These techniques enable imaging of subsurface structures, delineation of lithological boundaries, identification of alteration zones and mineralization, estimation of depth, characterization of physical properties, integration with other data sources, and targeting exploration efforts. Geophysical mapping greatly contributes to a comprehensive understanding of basement rock characteristics and aids in various applications, including resource exploration, engineering projects, and geological hazard assessments.

Magnetic surveys are a geophysical mapping technique that plays a significant role in mapping basement rocks. Magnetic surveys measure variations in the Earth's magnetic field caused by variations in the magnetic properties of subsurface rocks [88]. Basement rocks often exhibit different magnetic properties compared to overlying sedimentary or volcanic rocks. By measuring and mapping magnetic anomalies, geophysicists can identify areas with contrasting magnetic signatures, which can be indicative of different types of basement rocks or geological structures. Magnetic surveys help in delineating geological structures associated with basement rocks [89]. Fault zones, fractures, and other structural features can produce localized variations in magnetic properties. By analyzing the magnetic anomalies, geophysicists can infer the presence of these structures and map their orientations, extents, and relationships. Magnetic surveys provide valuable information about the structural framework and deformation history of the basement rocks.

Magnetic surveys aid in mapping the contacts between basement rocks and overlying sediments or volcanic covers. Basement rocks often have different magnetic properties compared to the younger rocks above them [90]. With these techniques, detection of abrupt changes in the magnetic field intensity or direction provides clue for the presence of contacts. Mapping these contacts is crucial for understanding the subsurface geology and stratigraphy. The methodology is effective and can identify intrusions and igneous activity associated with basement rocks. Intrusive bodies, such as granites or diorites, often exhibit distinctive magnetic signatures due to their high concentrations of magnetic minerals, such as magnetite [91]. By mapping magnetic anomalies, geophysicists can locate and delineate these intrusive bodies, providing insights into the distribution and nature of basement igneous activity. Magnetic surveys contribute to mineral exploration by identifying magnetic minerals associated with mineralization in basement rocks. Certain ore deposits, such as iron, nickel, and magnetite-rich deposits, can produce significant magnetic anomalies [92]. Magnetic surveys help in locating and mapping these anomalies, providing valuable information for targeting mineral exploration efforts and assessing the potential for economic mineral deposits within the basement rocks.

Magnetic surveys can be integrated with other geophysical surveys, such as gravity, seismic, and electromagnetic surveys, as well as geological and geochemical data [93]. This integration allows for a comprehensive understanding of basement rock characteristics and improves the accuracy of mapping. By combining multiple datasets, geologists can refine interpretations, identify correlations between different data types, and create more detailed and reliable basement rock maps. Magnetic surveys contribute significantly to basement rock mapping by detecting magnetic anomalies, delineating geological structures, mapping basement contacts, identifying intrusions and igneous activity, aiding in mineral exploration, and integrating with other data sources. These surveys provide valuable information about the magnetic properties of basement rocks, helping geologists to understand the subsurface geology, structural framework, and mineral potential of the basement rock systems.

Gravity surveys are a geophysical mapping technique that has the capacity to enhance the mapping of basement rocks. They could measure variations in the Earth's gravitational field caused by variations in the density of subsurface materials [94]. Basement rocks often have different densities compared to the overlying sediments or volcanic rocks. By measuring and mapping gravity anomalies, geophysicists can identify areas with contrasting density signatures, which are indicative of different types of basement rocks or geological structures. Gravity surveys help in delineating geological structures associated with basement rocks. Fault zones, folds, and other structural features can cause variations in the density of the rocks, leading to gravity anomalies. By analyzing the gravity data, geophysicists can infer the presence of these structures and map their orientations, extents, and relationships [95]. Gravity surveys provide valuable information about the structural framework and deformation history of the basement rocks. This survey method aids in mapping the contacts between basement rocks and overlying sediments or volcanic covers. The application typically produces higher densities compared to the younger rocks above them. The technique detects any subtle abrupt changes in the gravity field, and when this is noticed then, there is the presence of some contacts. Mapping these contacts is crucial for understanding the subsurface geology and stratigraphy.

Gravity surveys are used to detect subsurface features associated with basement rocks, such as buried structures, basins, or intrusive bodies. Variations in density caused by these features can produce gravity anomalies. By mapping these anomalies, geophysicists can infer the presence of buried features and gain insights into their size, shape, and depth. Gravity surveys help in identifying hidden geological features associated with basement rocks. Gravity surveys contribute to mineral exploration efforts by identifying gravity anomalies associated with mineralization in basement rocks. Certain ore deposits, such as dense metallic minerals or mineralized bodies, can produce significant gravity anomalies. By mapping gravity anomalies, geophysicists can locate and delineate these anomalies, providing valuable information for targeting mineral exploration efforts and assessing the potential for economic mineral deposits within the basement rocks. Gravity surveys can be integrated with other geophysical surveys, such as magnetic, seismic, or electrical resistivity surveys, as well as geological and geochemical data [96]. This integration allows for a comprehensive understanding of basement rock characteristics and improves the accuracy of mapping. By combining multiple datasets, geologists can refine interpretations, identify correlations between different data types, and create more detailed and reliable basement rock maps. Gravity surveys contribute significantly to basement rock mapping by detecting gravity anomalies, delineating geological structures, mapping basement contacts, identifying subsurface features, targeting mineral exploration, and integrating with other data sources [95]. These surveys provide valuable information about the density variations and gravitational field, helping geologists understand the subsurface geology, structural framework, and potential mineralization associated with basement rocks.

Electrical resistivity surveys, also known as resistivity imaging or electrical resistivity tomography (ERT), are a geophysical mapping technique that plays a crucial role in mapping basement rocks. Basement rocks often exhibit different electrical resistivity values at different rock types [97]. The technique has the capacity to measure the subsurface resistivity distribution, which is related to the rock's composition, porosity, and fluid content. When data is collected and analyzed different rock types within the basement complex can be discriminated against. Because of this the method is suitable for mapping lithological variations and deriving subsurface geological information. Several facilities information could be delineated, examples are fault zones, fractures, and other structural features. By mapping resistivity anomalies, geophysicists can infer the presence of rock structures and extend search to their orientations, extents, and relationships [98]. This information is vital for understanding the structural framework and deformation history of the basement rocks.

The method is also used for identifying alteration zones and potential mineralization associated with basement rocks [99]. However, there are certain mineral deposits that induce changes in the electrical resistivity due to mineralogical alterations or the presence of conductive fluids [100]. Resistivity anomalies can be indicative of alteration zones or mineralized bodies within the basement rocks. Mapping these anomalies helps in targeting mineral exploration efforts and assessing the potential for economic mineral deposits. Electrical resistivity surveys provide insights into subsurface heterogeneities within the basement rocks [101]. Variations in resistivity can indicate changes in rock composition, fracture networks, or fluid-filled cavities. By imaging the resistivity distribution, geophysicists can identify zones of high or low resistivity that may correspond to different lithological units, structural features, or fluid-filled pathways. This information aids in understanding the subsurface architecture and the distribution of geological features associated with basement rocks.

Multiple location measurements undertaken with resistivity surveys can be used to infer the depth of the interface between the basement rocks and overlying layers [102]. This estimation is valuable for understanding the subsurface geology and stratigraphy and aids in accurate mapping of the basement rock boundaries. Furthermore, these kinds of surveys when integrated with other geophysical surveys, such as seismic, magnetic, or gravity surveys, as well as geological and geochemical data, become very beneficial for stratigraphy identification. This integration allows for a comprehensive understanding of basement rock characteristics and improves the accuracy of mapping. By combining multiple datasets, geologists can refine interpretations, identify correlations between different data types, and create more detailed and reliable basement rock maps. Electrical resistivity surveys contribute significantly to basement rock mapping by differentiating rock types, delineating geological structures, identifying alteration zones and mineralization, imaging subsurface heterogeneities, estimating depths, and integrating with other data sources [103]. These surveys provide valuable information about the subsurface resistivity distribution, which helps geologists understand the lithological variations, structural framework, alteration patterns, and potential mineralization within the basement rock systems.

3.3 Geochemical Analysis Techniques for basement lithological mapping

Geochemical analysis is necessary in basement rock mapping because it enables rock classification, source determination, petrogenesis and metamorphic studies, mineral exploration, environmental assessment, and integration with other data sources. Geochemical data provide valuable insights into the composition, origin, history, and potential resources of the basement rocks, aiding in geological interpretation, resource assessment, and environmental management [104]. The X-Ray Fluorescence (XRF) analysis is crucial in basement rock mapping for determining elemental compositions, identifying geochemical signatures, characterizing mineralogy and alteration, conducting petrogenetic studies, mapping geochemical variations, and integrating data with other sources. XRF analysis provides valuable insights into the geochemical characteristics of basement rocks, aiding in geological interpretation, mapping, and understanding the geological processes involved in their formation and evolution [105]. The X-Ray Diffraction (XRD) analysis is essential in basement rock mapping for mineral identification, quantification, and characterization, detecting polymorphism and crystallographic orientation, studying alteration and diagenesis, analyzing rock texture and fabric, and integrating data with other sources. XRD analysis provides valuable insights into the mineralogical composition, rock properties, and geological processes associated with basement rocks, aiding in geological interpretation, mapping, and understanding their formation and evolution [106].

4. Applications of Lithological Mapping for Basement rocks

Lithological units mapping has been beneficial for deriving information of basement rocks revealing the composition, distribution, and characteristics of different lithological units within the subsurface. Lithological units show boundaries, variations, constraints to structures, enabling mineral resources and groundwater assessment, while addressing environmental implications. The benefits of lithological information are discussed in four specific areas of applications as follows:

4.1 Tectonic history and structural evolution studies

The role of tectonic history and structural studies in basement rock mapping is crucial for understanding the geologic history and subsurface characteristics of an area. The tectonic history of a region provides essential context for interpreting the structural features and distribution of basement rocks. The tectonic information enables researchers to understand the surface expression because tectonic activities have great influence on the surface topography and the features around. By that, we categorize mountain ranges, valleys, and fault lines [107]. The second aspect is the crustal evolution where the tectonic information enables understanding of what shaped the crust and eventually the origin and basement information [108]. The historical information in the other hand enables knowledge of the geologic time frame and of the paleogeography of the area of study [109]. Furthermore, structural information focusses on the deformational history and the rock fabric orientation [110]. Therefore, when tectonic, historical, and structural information are combined, provides a holistic understanding of an environment. **Figure 6** illustrates the implication of integration.

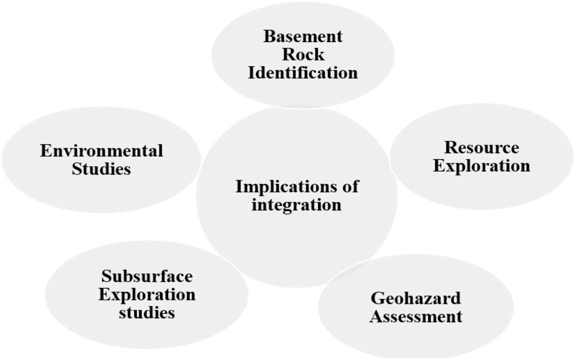

Figure 6. Results of integration for tectonic history and structural evolution studies.

4.2 Mineral exploration and resource assessment

Mineral exploration and resource assessment are closely linked to basement rock mapping with a multidisciplinary approach, where the geological, geophysical, geochemical and remote sensing data are combined together. The integration enhances the accuracy of the mineral exploration and resource assessment process as well as guiding the activities of development plans. **Figure 7** illustrates the aspects and methods of understanding basement rocks by revealing regions of mineralization.

4.3 Hydrology and groundwater resources mapping

Hydrology and groundwater resources studies contributes to deeper knowledge of basement rock, so that information concerning water-bearing properties, flow patterns, and potential aquifer systems associated with basement rocks are derived. The wa-

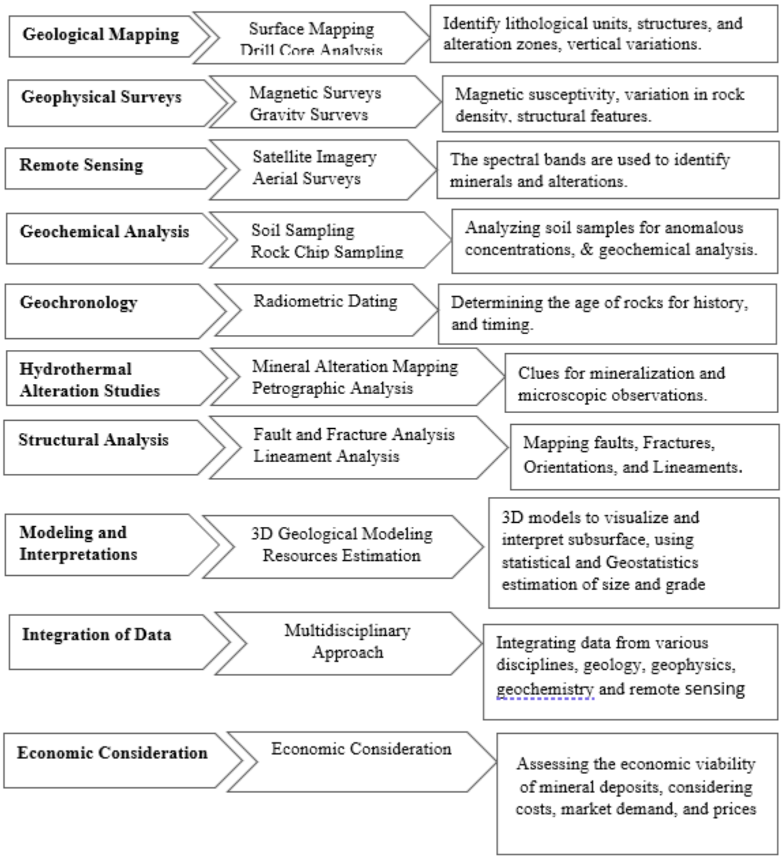

Figure 7. Illustrates the mineral exploration and resource assessment.

ter-bearing properties become useful in identifying the lithological variations, fractures, and structural features that influence the water-bearing properties of the subsurface [111]. Knowledge about the composition and structure of basement rocks, enable assessment of porosity, permeability, and storage capacity, which are very necessary information for groundwater occurrence and flow [112]. Mapping the water-bearing properties of basement rocks assists in characterizing aquifers, delineating recharge zones, and understanding the potential for groundwater storage and extraction. Likewise, determining the flow patterns and hydrologic connectivity within the subsurface, provide link to fractures and faults within a basement. Despite that rocks can act as conduits or barriers to groundwater flow, they influence the movement and distribution of water. By mapping the fracture networks and structural features, geologists can identify preferential flow paths, groundwater recharge areas, and potential areas of groundwater discharge [113]. Understanding the flow patterns and hydrologic connectivity is essential for sustainable management of groundwater resources and predicting the impacts of human activities or natural processes on water availability.

Basement rock mapping contributes to the identification and delineation of aquifer systems associated with basement rocks [114]. Aquifers are underground formations capable of storing and transmitting water, and they can occur within fractures, weathered zones, or other water-bearing structures within basement rocks. By mapping the lithological variations, fractures, and structural features, geologists can identify potential aquifers and assess their extent, productivity, and sustainable yield [115]. Aquifer mapping and resource assessment assist in evaluating the groundwater potential, estimating available water resources, and guiding water supply planning and management. They are still relevant to assessing geological hazards and water quality issues related to groundwater resources. Certain geological features within basement rocks, such as faults or unstable rock masses, can pose risks to groundwater quality and availability [116]. Mapping these hazards and understanding their interactions with groundwater systems helps in identifying areas prone to contamination, saltwater intrusion, or other water quality concerns [117]. It also contributes to mitigating risks associated with geological hazards, such as land subsidence or groundwater-related natural disasters. Hydrology and groundwater resources information are key elements used for basement rock mapping, by providing deeper knowledge on water-bearing properties, flow patterns, aquifer systems, and water quality considerations associated with basement rocks. This knowledge supports sustainable management and utilization of groundwater resources, facilitates water supply planning, and helps in assessing and mitigating geological hazards related to groundwater.

4.4 Environmental and land use planning studies

Environmental and land use studies are contributory to basement rock mapping as valuable insights into the geological characteristics of an area are derived in the process. Other information on geological formations, include mineral deposits, and potential environmental impacts. Understanding the composition and distribution of basement rocks helps in identifying areas with unique ecological features, such as habitats, protected areas, or areas of high biodiversity [118]. This knowledge supports the conservation and management of environmental resources, including forests, wetlands, and sensitive ecosystems, by integrating geological data with ecological studies. Basement rock mapping is valuable for land use planning and management purposes. By mapping the geological characteristics, landforms, and topography associated with basement rocks, it becomes possible to identify suitable land uses, such as agriculture, forestry, or urban development. Understanding the limitations and potentials of the land based on basement rock types and associated geological hazards allows for informed decision-making regarding land use zoning, infrastructure development, and natural resource management. Basement rock mapping plays a crucial role in assessing geological hazards and their potential impacts on the environment and land use [119]. Certain geological features associated with basement rocks, such as faults, landslides, or karst formations, can pose hazards to infrastructure, human settlements, and the environment [120]. Mapping these hazards and their interactions with basement rocks helps in identifying areas prone to geological risks, including earthquakes, landslides, sinkholes, or groundwater-related issues. This information is essential for hazard mitigation, emergency planning, and the sustainable development of the land.

Basement rock mapping is an important component of environmental impact assessments (EIAs) for various development projects. EIAs evaluate the potential environmental consequences of proposed activities, such as mining, construction, or infrastructure projects. By understanding the geological context provided by basement rock mapping, it becomes possible to assess the potential impacts of these activities on groundwater resources, surface water quality, ecosystems, and geological stability. This information aids in making informed decisions, implementing mitigation measures, and ensuring sustainable development practices. Environmental and land use studies add impetus to basement rock mapping by integrating geological information with ecological assessments, land use planning, and environmental impact assessments. This interdisciplinary approach supports the sustainable management of environmental resources, land use activities, and the identification and mitigation of geological hazards [121,122].

5. Remote sensing of basement lithologies using contextual lithological mapping approach for semi-arid regions

Considering the semi-arid environment, the basement rocks could be accurately mapped using the lithology's as the key elements. However, the contextual approach to lithological mapping involves considering not just the specific characteristics of the individual rocks available but also their surroundings information, the environmental factors, and their spatial relationships. While this concept of adding contextual analysis in remote sensing recent studies, it has been a fundamental aspect of geological studies. The application of the contextual to lithological mapping, especially in semi-arid regions using remote sensing is advancing due to technological and methodological developments. In recent research, the of combination of spectral analysis, integration of ground truthing data and hybrid mapping methods is dominating. **Table 5** presents the information on how involving the contextual becomes of advantage.

Mapping rocks with satellite-based sensors is a challenging approach and must fulfil some specific capabilities to be functional. The basic is in penetrating through overlying materials and structures. Which is why it is difficult to get a single sensor that would be perfect for all geological situations, the following factors are considered very necessary for choosing the data to apply. **Figure 8** illustrates satellite sensors for geological applications.

Geographic Information System (GIS) can contribute significantly to mapping basement rocks by providing powerful tools for data management, analysis, visualization, and interpretation [123]. GIS contributes most prominently through data integration, spatial analysis, 3D visualization, map production, data validation, and spatial decision support. It enables the integration and analysis of diverse datasets, provides tools for spatial analysis and visualization, supports map production and data validation processes, and facilitates informed decision-making related to basement rock mapping [124,125]. GIS performs data integration and data fusion in geological operations [126]. It enables the integration, analysis, and visualization of various data types and layers related to specific aspect of geology e.g. basement rocks mapping, facilitating a comprehensive understanding of the subsurface geology. GIS allows for the integration of diverse datasets, including geological maps, geophysical surveys, borehole data, remote sensing imagery, and topographic information. By organizing and structuring these datasets spatially, GIS enables the identification and exploration of relationships between different geological features and their spatial distribution [127]. This integration helps in building a more complete and accurate representation of basement rocks and their characteristics.

Table 5. Recent technique for lithological mapping of rocks.

S/N	Mapping Aspect	Description	Evolution of contextual Approach	Key components of contextual Approach	Benefits of Contextual properties	Future Prospects
1	Hyperspectral Imaging	Captures detailed spectral information for surface composition.	Transition from single band to multispectral analysis.	Multispectral analysis for subtle mineral variations.	Understand subtle mineral variations in different rock types.	Advanced ML for automated analysis.
2	Spectral Analysis	Identifies unique spectral features for lithological units.	Integration of multiple spectral bands for analysis.	Understanding how spectral variations correlate with lithology.	Helps in distinguishing specific mineral compositions accurately.	Enhanced spectral libraries for better accuracy.
3	Mineral Mapping	Maps the distribution of specific minerals in basement rocks.	Considering environmental influence on spectral signatures.	Relates spectral signatures to known mineralogy.	Enables identification of mineral-rich zones or potential deposits.	Improved identification of mineral deposits.
4	Alteration Mapping	Identifies areas of alteration or mineralization in rocks.	Incorporates geological context for alteration mapping.	Analysis of spectral changes due to alterations.	Pinpoints to potential geological features or mineralization areas.	Enhanced understanding of subsurface geology.
5	Topographic Mapping	Considers topography's influence on lithological variations.	Emphasizes spatial relationships between lithology and topography.	Integration of topographic data with spectral information.	Provides insight into how topography affects rock exposure.	Better predictions of subsurface geology.
6	Advanced Data Analysis	Uses AI and ML for automated spectral classification.	NA	NA	Automates identification, enhancing speed and accuracy	NA
7	Integration of Field Data	Validates remote sensing results with field samples.	NA	NA	Confirms accuracy, reducing potential misinterpretation	NA
8	Challenges	Weather variability, sparse vegetation, resolution scale.	NA	NA	Understanding limitations aids in optimizing data collection	NA
9	Benefits	Accurate mineral identification and creates understanding of subtle variations.	Transition from single band to multispectral analysis. Environmental influence on spectral signatures.	Multispectral analysis, spatial and spectral correlation.	Pinpointing mineral-rich zones. Improved subsurface understanding.	Enhanced accuracy through spectral libraries. Automated analysis with advanced ML.
10	Prospects	Enhanced ML algorithms for automated analysis.	More comprehensive spectral libraries for accuracy.	Advancements in spatial and spectral correlation.	Advanced automated analysis for faster mapping.	Improved identification of hidden mineral deposits.

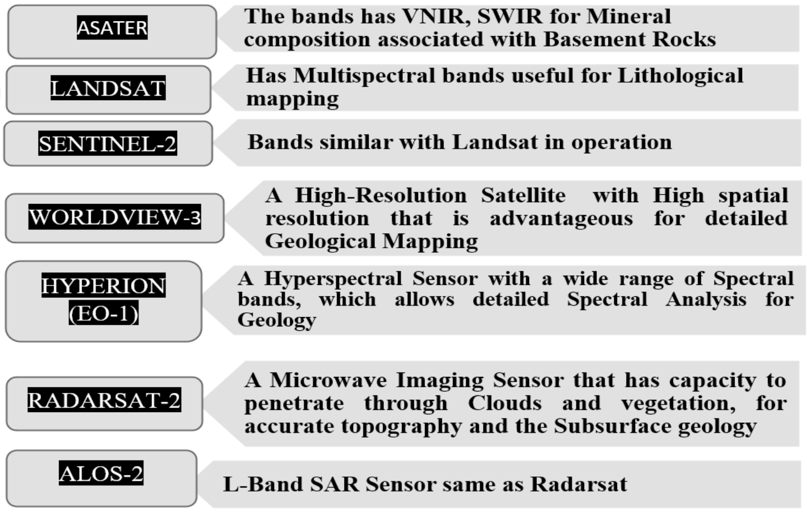

Figure 8. Satellite sensors for geological applications.

GIS enables the fusion of different data sources and types, including vector data, raster data, and attribute data. It allows for the integration of geological, geophysical, and geochemical datasets, enhancing the understanding of subsurface geology [128]. Data fusion techniques in GIS can involve combining and analysing multiple datasets to generate new information or insights. For example, combining geological maps with geophysical data can provide a better understanding of subsurface structures and lithological variations within basement rocks. GIS provides a suite of spatial analysis tools that aid in understanding and interpreting basement rock data [129,130]. These tools allow for the measurement, comparison, and modelling of geological parameters, such as thickness, depth, slope, and orientation. GIS can perform spatial interpolation techniques to estimate values between data points, enabling the creation of continuous surfaces representing basement rock properties [131]. Spatial analysis in GIS helps in identifying trends, anomalies, and patterns within basement rock data, facilitating the interpretation and mapping of geological features.

According to [132], the use of GIS operation makes room for maps creation, cross-sections, and 3D representation visualization capabilities. It also creates the spatial relationships between geological features, identify trends, patterns, and potential correlations [133]. GIS-based mapping tools enable the creation of thematic maps, highlighting the distribution of lithologies, faults, fractures, or other basement rock characteristics. These visual representations aid in communication, decision-making, and the presentation of basement rock data to stakeholders. GIS serves as a decision support system for basement rock mapping. By integrating and analysing various data layers, GIS provides a comprehensive understanding of subsurface geology, enabling informed decision-making regarding resource exploration, environmental management, and land use planning [134]. GIS-based models and simulations can help evaluate different scenarios, assess risks, and optimize strategies for basement rock mapping and related activities [135]. GIS techniques have been very contributory to basement rock mapping by facilitating data integration, fusion, spatial analysis, visualization, and decision support. It enables the integration of diverse datasets, analysis of spatial relationships, visualization of basement rock characteristics, and informed decision-making for resource exploration, environmental management, and land use planning.

Several mapping techniques are put together in recent research studies and the results of which are reported to have greater fidelity than single operations [136]. In the geological domain, there are many techniques available such as geological mapping, geophysical surveys (e.g., gravity, magnetic, electrical), remote sensing, and drilling. Some of these provide complementary information, while on the other hand improving accuracy and reliability. Integrating mapping techniques provides multi-dimensional information about basement rocks. Each mapping technique offers unique insights into different aspects of the subsurface, such as lithology, structure, alteration, mineralization, and fluid flow. By integrating data from various techniques, geologists can analyze and interpret the multi-dimensional characteristics of basement rocks, leading to a more comprehensive understanding of their geological properties [137,138]. One of the areas of contribution is validation and cross-verification of data. Despite that every method has inherent limitations, and uncertainties, integration and iteration improve the robustness and reliability of the final mapping results. Every of the integration procedure, spatial and depth resolution capabilities are exploited. This makes the process of delineating lithological variations, structural features, and other geological characteristics at a finer scale [139].

6. Interdisciplinary collaborations for enhancement of applications

Interdisciplinary collaboration is one of the ways to enhance applications in geologic mapping, as it is in the research world. Bringing together expertise from various disciplines addresses complex issues in research [140]. Any act of interdisciplinary collaboration has to do with integrating diverse datasets and information from different sources. At the end of any analysis, with the process of integration, a more holistic understanding is created including subsurface geology, and many other fields. Every discipline that operates this unique perspective, methodologies, or interpretation techniques, leverage of expertise is of nuanced consequence [141]. There are many advantages of applying multidisciplinary interpretation, one of such is uncovering complex processes, in geology identifying mineral resources, and understanding broader implications of basement rock mapping. Further fostering the development of innovative methodologies and techniques encourages the use of specialized tools, applying analytical approaches, and undertaking technologies that could be adapted and combined to tackle specific challenges.

Taking a specific discipline like consideration of basement rock mapping, which is a complex geological phenomenon, the interdisciplinary collaborations will expose difficult phenomena like tectonic events, mineralization processes, groundwater dynamics, and environmental interactions. And so is every other discipline such as hydrologists, geochemists, ecologists, and others. This process supports integrated decision-making processes, it involves stakeholders from different disciplines, such as government agencies, industry professionals, environmentalists, and local communities, making a more inclusive and balanced decision-making process to be be achieved [142]. Collaborative discussions and knowledge exchange enable the consideration of multiple perspectives, values, and priorities, leading to more informed decisions regarding resource exploration, environmental management, land use planning, and sustainable development [143]. Summarily, interdisciplinary collaboration enhances the applications for basement rock mapping by promoting comprehensive data integration, enhancing data interpretation, fostering innovation in methodologies and techniques, addressing complex geological questions, and enabling integrated decision-making. This collaborative approach ensures a more holistic and robust understanding of basement rocks, their characteristics, and their implications for various sectors, contributing to more effective and sustainable management of geological resources and the environment.

6.1 Challenges and limitations

Data integration, quality control, scale effects and resolution as well as interpreting uncertainties are the common challenges that cause limitation in basement rock mapping. These are described as follows. Data that is used in mapping comes with varying formats, this is an issue of incompatibility, the resolutions, and the quality levels and not the same, which creates challenges at the points of integration [144]. However, they must be harmonized and standardized to make effective fusion. Coupled with this are data gaps, which emanate from missing and incomplete data, which make data integration very difficult to perform and produce seamless results. Data quality on the other hand is about variations and accuracy across the many sources of the datasets. This impacts on the reliability and on the validity of the results. There must therefore be proper validation, calibration, and verification of the datasets put together [145].

Scale and resolution pose challenges in data integration and quality control due to the following factors (**Figure 9**). Addressing these challenges requires careful consideration of data preprocessing techniques, resampling methods, data validation procedures, and quality control measures. It is crucial to assess the compatibility, accuracy, and representativeness of integrated datasets to ensure reliable and meaningful analyses and interpretations.

Addressing uncertainties and interpretation assessment challenges in data integration and quality control requires rigorous quality assurance and quality control (QA/QC) procedures. These procedures involve thorough data validation, uncertainty quantification, sensitivity analysis, and documentation of assumptions and limitations. It is important to communicate and document uncertainties and limitations associated with the integrated dataset to ensure transparency and enable informed decision-making (**Figure 10**).

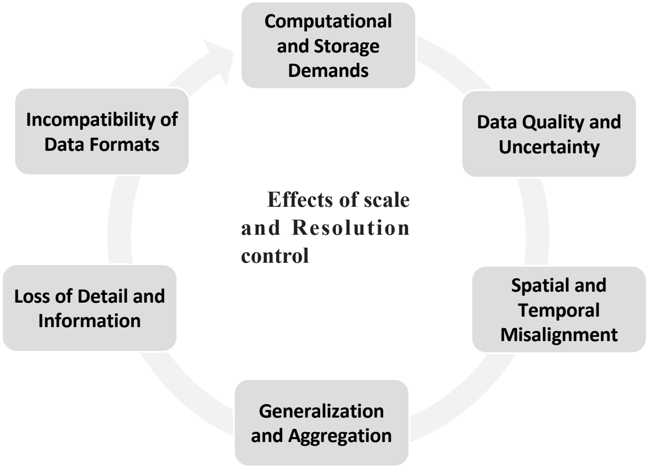

Figure 9. Effects of scale and resolution control on lithological mapping.

Figure 10. Uncertainties and interpretation assessments. Source: [146].

7. Conclusions

The future direction in basement rock mapping is in the integration of artificial intelligence (AI), and machine learning (ML) capabilities developing in the areas of advances in mapping technologies. Basement rock mapping is very beneficial as it plays a vital role in creating understanding of the characteristics of geological deposits, and the history of the rocks. Identification, classification, and the spatial representation of the categories of rocks at varying scales is carried out. The data of various sources are in the process integrated creating interdisciplinary cross fertilization and collaborations, advanced techniques of mapping can be unraveled to handle complex terrain and regions with political difficulties and inaccessible. The knowledge of the basement rocks leads to deciphering of tectonic histories, structural evolutions, and how the landscapes are shaped from time to time. Variations in vertical arrangement of deposits, providing better understanding of areas of exploration of underground water, hydrocarbons, and solid mineral resources. All these are good support for informed decision making in many fields of research. While mapping provides valuable data for planning and resource potentialities, it also helps in identifying areas of geological hazards, vulnerability, and risks. The integration of artificial intelligence, machine learning and other emerging techniques create enhancement and accuracy of presentation. Issues related to integration, quality control, scale, interpretation, and uncertainty are expected to be given adequate consideration. There is in progression, automation in image processing capacities which inadvertently provide and unveil hidden complexities in the data and the sub-surface. The future holds great promise of accurate and informed decision-making exercises, collaborations, and significant understanding of the world we are living in.

Author Contributions

"Conceptualization, D.J.H., M.H; investigation, A.B.P, J.H.; writing—original draft preparation, D.J.H.; writing—review and editing, A.B.P., M.H. J.H; supervision, M.H and A.B.P; All authors have read and agreed to the published version of the manuscript."

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are contained within the article.

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