Review

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Geological Remote Sensing of Korea

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Abstract: This review paper provides a comprehensive overview of advancements in geological remote sensing in Korea, based on the research published in the Korean Journal of Remote Sensing (KJRS). The review encompasses critical geological domains, including lineament analysis, rock and mineral remote sensing, landslide detection, volcanic activity monitoring, earthquake assessment, and gravity studies. The content is organized chronologically, allowing for a detailed examination of the evolution of remote sensing techniques and their applications by KJRS authors. This review emphasizes significant contributions that have improved the accuracy, reliability, and predictive capabilities of geological studies through the application of remote sensing. Additionally, the paper highlights the integration of diverse remote sensing tools—ranging from satellite imagery and spectral analysis to advanced machine learning models—which collectively have facilitated a more profound understanding of geological phenomena. The insights derived from these studies are essential for the effective management of natural resources, disaster preparedness, and environmental conservation efforts.

Keywords: Geology, Lineament, Rock, Landslide, Earthquake, Volcano, Gravity

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1. Introduction

Remote sensing technologies have revolutionized the field of geological studies by providing advanced tools and methodologies for the analysis of Earth's surface and subsurface features. In Korea, the application of remote sensing has significantly enhanced our understanding of various geological phenomena, from the identification and analysis of lineaments to the monitoring of seismic activities and volcanic movements. This review paper overviews the contributions of remote sensing technologies across several key geological domains, drawing from a rich body of research published in the Korean Journal of Remote Sensing (KJRS).

The sections in this review cover a wide range of applications, each highlighting the unique contributions and advancements made in the respective fields. The first section, "Lineament" explores the use of satellite imagery and Geographic Information System (GIS) techniques to identify and analyze geological lineaments, which are crucial for understanding fault systems and groundwater potential zones. This is followed by a comprehensive overview of "Rock and Mineral," which examines the spectral analysis of geological materials and the identification of mineralized zones, providing critical insights into the resource management and exploration sectors.

In the subsequent section on "Landslide," the focus is on the detection, monitoring, and prediction of landslides, which is an increasingly important area of study in the context of climate change and its impact on land stability. The use of advanced remote sensing technologies such as Interferometric Synthetic Aperture Radar (InSAR) and machine learning models has been instrumental in developing accurate landslide susceptibility maps, which are vital for disaster management and mitigation strategies.

The "Volcanic" section focuses on the monitoring of volcanic activities, particularly in relation to Mt. Baekdu, a significant geological feature with implications for both Korea and other

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countries. The “Earthquake” section provides an in-depth analysis of how remote sensing technologies have been utilized to monitor seismic activities, assess earthquake impacts, and enhance our understanding of the complex dynamics of tectonic movements.

Finally, the section on “Gravity” examines the use of gravity measurements and satellite data to study Earth’s gravity and magnetic field and its variations, which are essential for understanding geodynamic processes and their effects.

This review aims to provide a comprehensive overview of the state-of-the-art in remote sensing applications in Korea’s geological studies, highlighting both the achievements and the ongoing challenges in this rapidly evolving field. The insights gained from these studies not only contribute to the scientific community but also have practical implications for resource management, disaster preparedness, and environmental protection in Korea and beyond.

2. Materials and Methods

The primary material for this study consisted of abstracts from journal papers published in the KJRS. A systematic search was conducted in the KJRS database. The search was aimed at identifying abstracts related to various aspects of geological remote sensing, including but not limited to lineament analysis, rock and mineral mapping, landslide detection, earthquake monitoring, and gravity studies.

The search was guided by specific keywords and search terms relevant to the study’s objectives. The keywords include lineament, gravity, landslide, earthquake, rock, mineral, and groundwater. The choice of these keywords was based on their frequent occurrence in the literature and their significance in the context of geological remote sensing. The use of broad and specific terms ensured that the search would capture a comprehensive set of studies, encompassing a wide range of methodologies, study areas, and remote sensing technologies.

Fig. 1 shows the number of yearly papers related to geological remote sensing published in KJRS from 1984 to 2024. A total of 97 papers were selected, categorized as follows: lineament (19 papers), rock and mineral (17 papers), landslide (19 papers), volcano (24 papers), earthquake (17 papers), and gravity (7 papers). The total count sums up to 103 due to some review papers being classified under multiple categories. The research focus has shifted considerably over time, with early emphasis on lineament and rock studies in the late 1980s and 1990s. A noticeable transition occurred in the mid-2000s, marked by a spike in volcano research. Since 2017, the number of papers on landslides and earthquakes has increased significantly, making them dominant topics in recent years. Gravity research remains limited, and the overall distribution suggests that geological hazards like earthquakes and landslides have become a growing priority in recent decades.

3. Geological Remote Sensing of Korea in KJRS

This section outlines the evolution of geological remote sensing as documented in the KJRS. It is organized into subsections on lineament, rock and mineral, landslide, volcano, earthquake, and

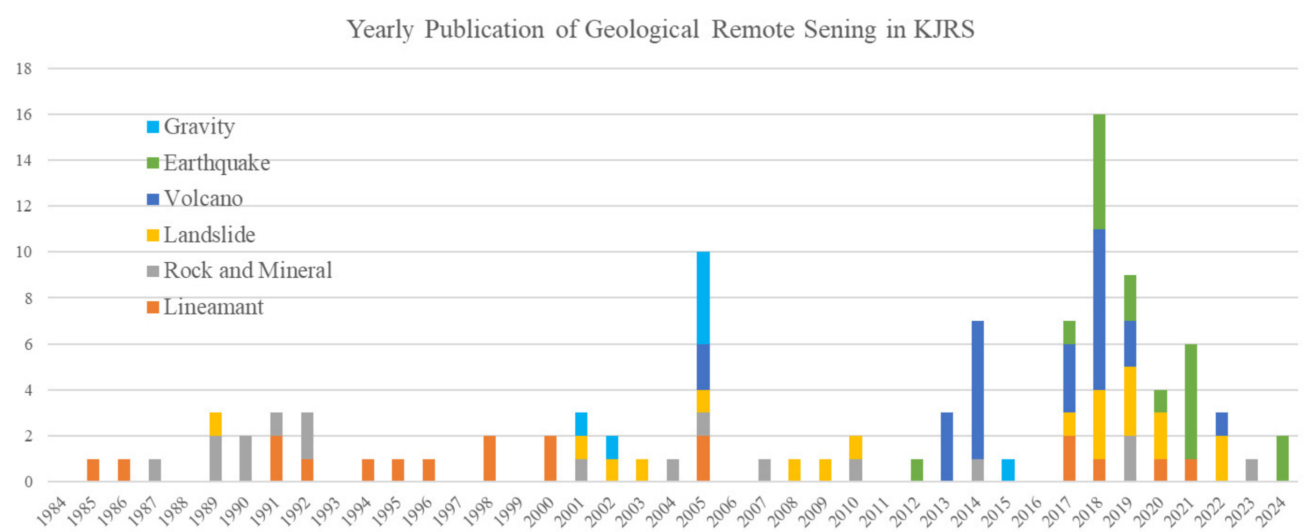

Fig. 1. The yearly number of papers related to geological remote sensing published in KJRS from 1984 to 2024.

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gravity studies. The journal papers within each subsection are presented in chronological order.

3.1. Lineament

Lineament analysis plays a crucial role in geological and hydrological studies, particularly in understanding fault systems, groundwater potential zones, and other geological structures. Remote sensing technology has enabled more efficient and extensive extraction and analysis of lineaments. This section reviews the key studies published in the KJRS related to lineament remote sensing in Korea, highlighting the methodologies and findings of these studies, presented in chronological order.

Kang et al. (1985) applied digital image processing techniques to analyze the Seoul-Dongducheun lineament, a significant geological feature associated with the Choogaryong fault system. The identified lineaments corresponded with known geological trends, providing valuable insights into the structural geology of the area. Kang et al. (1986) used Landsat Thematic Mapper (TM) data to study mineralized zones in the Ryeongnam area, a major mineralized region in Korea. The research applied various image processing techniques, finding spatial filtering most effective for lineament extraction and ratio methods useful for detecting altered zones. Kang et al. (1991) analyzed lineaments and circular/arc structures on Landsat TM imagery covering the Korean Peninsula. The study identified predominant lineament trends and categorized circular/arc structures based on their origins, such as volcanic activity, granite intrusion, and structural features.

Chi (1991) conducted a study to map groundwater potential areas using GIS integrated with Landsat TM data. The study found a strong correlation between lineaments and groundwater wells, identifying potential sites for groundwater extraction. In a continuation of his previous work, Chi (1992) aimed to improve groundwater potential area mapping using GIS and thematic maps such as slope, geologic, and soil maps. The study combined these maps with lineament data to create a suitability map for groundwater exploration. Chi (1994) focused on extracting groundwater potential areas by analyzing remotely sensed satellite data. The study revealed that 81% of operational wells were related to lineaments, with 51% located at lineament intersections. The study emphasized the importance of lineament features in groundwater exploration.

Lee and Chi (1995) focused on the integration of multiple geological lineament-related data sets using fuzzy set theory. The research integrated various data sets, including geological maps, satellite images, and drainage patterns, to produce a more comprehensive and reasonable interpretation of geological lineaments. The study demonstrated the utility of fuzzy set theory in the spatial integration of diverse geological data, providing a more holistic approach to geological analysis. Kim et al. (1996) developed a technique to assess geological lineaments using remotely sensed data and Digital Elevation Models (DEMs). The study compared lineaments extracted from TM images, DEMs, and geological maps, finding that using relief-shadowed DEMs helped mitigate the look direction bias in satellite images.

Won (1998) explored the use of the Radon transform in two-dimensional filtering for digital image processing, particularly in lineament analysis. The study demonstrated that applying one-dimensional convolution in the Radon space, followed by inverse Radon transform, could effectively enhance features like ship wakes in SAR images and reduce sea speckles. Won et al. (1998a) developed a new algorithm for automatic lineament extraction from Landsat TM images, specifically tailored for geological applications. The Dynamic Segment Tracing Algorithm (DSTA) was designed to handle various topographic conditions typical of Korea. The study also introduced additional algorithms using Hough Transform to enhance lineament detection. The developed algorithms were successful in extracting geological lineaments in both alluvial plains and mountainous regions, improving the accuracy of geological interpretations.

Won et al. (1998b) investigated the geological lineaments and spring water distribution on Jeju Island using Radarsat SAR imagery. The study found that combining SAR and TM images enhanced the detection of lineaments, particularly in areas where lineaments were poorly developed. The research also explored the challenges of detecting spring water using remotely sensed images, highlighting the need for careful selection of SAR parameters in such applications.

Kim et al. (2000) evaluated the use of lineaments for interpreting regional geological structures in the Euiseong Sub-basin. The study extracted lineaments from Landsat-5 TM images and correlated them with surface geological features mapped in the field. The primary directions of the lineaments were consistent with known faults and geological structures, demonstrating the utility of satellite lineament analysis in understanding large-scale geological formations. Hong et al. (2000) quantitatively analyzed the look-direction bias in SAR images, which affects the visibility of geological lineaments. By comparing lineaments detected in SAR and TM images, the study demonstrated that lineaments perpendicular to the radar look direction were more prominent, while those parallel were less visible.

Heo and Lee (2005) applied the Weight of Evidence (WofE) technique within a GIS framework to estimate groundwater yield characteristics in the Pocheon area. The study considered multiple factors, including lineament density, geology, and drainage patterns, to produce a feasibility map indicating groundwater potential. Baek and Park (2005) applied fuzzy logic-based data integration to map geothermal potential zones in Jeju Island. The study collected various thematic maps, such as geological maps, drainage density, lineament density, and geophysical survey data, and integrated them using fuzzy logic to identify potential geothermal areas. The results indicated that lower density of lineaments, along with other geological and geophysical factors, correlated with higher geothermal potential.

Jo et al. (2017) analyzed the relationship between lineaments and earthquake epicenters in the Geochang region using hotspot analysis. The study extracted lineaments from Landsat 8 imagery and correlated them with earthquake epicenters, finding significant overlaps in high-density lineament areas.

Lee (2017) reviewed remote sensing studies focused on groundwater resources, highlighting methods to analyze groundwater storage and dynamics. The review discussed the use of geological lineament analysis, airborne magnetic surveys, and DEM analysis in understanding groundwater systems. The study also emphasized the potential of Gravity Recovery and Climate Experiment (GRACE) and InSAR technologies in quantifying groundwater storage changes, though limitations in sensor accuracy and scale were noted.

Jeong et al. (2020) studied the variations in tidal channels in the Sihwa reclaimed land using high-resolution multispectral satellite imagery from KOMPSAT. The study applied various image processing techniques, including Principal Component Analysis (PCA) and Artificial Neural Networks (ANN), to extract tidal channel lineaments. The results demonstrated the effectiveness of high-resolution satellite imagery in detecting and analyzing tidal channels.

Gwon et al. (2021) reviewed various remote sensing techniques used in active fault investigations. The study covered satellite and airborne remote sensing, InSAR, and LiDAR, discussing their applications in identifying and analyzing active faults. The paper also addressed challenges in DEM generation and introduced new techniques like the Relief Ratio Index Model (RRIM) to overcome these issues. The review emphasized the importance of selecting appropriate remote sensing methods based on specific research objectives and the limitations of each technique in different geological settings.

Park et al. (2018b) examined the impact of DEM spatial resolution on automated lineament extraction. The study used different DEM resolutions, including SRTM and TerraSAR-X, to extract lineaments and found that higher resolutions provided more detailed lineament data. The study demonstrated that the density of extracted lineaments is proportional to the DEM's spatial resolution, underscoring the need for careful selection of DEMs in lineament studies for accurate geological analysis.

The research reviewed in this section underscores the critical role of remote sensing in the analysis of geological lineaments in Korea. From early studies that explored the extraction of groundwater potential areas to more recent developments in automated lineament extraction and fuzzy logic-based data integration, these studies highlight the evolution and increasing sophistication of remote sensing technologies in geological research. The integration of satellite imagery, DEMs, GIS, and advanced image processing techniques has greatly enhanced the ability to map and analyze lineaments, providing valuable insights into Korea's geological structures, groundwater resources, and geothermal potential. As remote sensing technologies continue to evolve, their application in lineament studies will undoubtedly expand, offering even more precise and comprehensive tools for geological exploration and hazard assessment.

3.2. Rock and Mineral

The study of rocks and minerals through remote sensing has become increasingly important in Korea, particularly in geological mapping, mineral exploration, and understanding the spectral characteristics of various geological materials. This section reviews key studies published in the KJRS related to rock and mineral remote sensing in Korea, highlighting the methodologies and findings of these studies.

Kang and Chi (1987) conducted a study to identify the most effective spectral channels for distinguishing geological materials in the Yangsan-Dongrae fault area using a portable radiometer. The study focused on pyrophyllites, andesites, granite, granodiorite, and silicified sedimentary rocks. The research found that altered rocks exhibited higher reflectance compared to unaltered rocks, and specific absorption features were identified for pyrophyllite, making certain Landsat TM bands particularly useful for discriminating these rocks. Kang and Chi (1989) explored the application of Landsat TM data for geological mapping and detecting mineralized zones in the Kyongju-Pohang area. The research used radiometric measurements and principal component analysis to differentiate between various rock types, including granites, andesites, and altered rocks.

Park and Seo (1989) applied the Iterative Self-Organizing Data Analysis (ISODATA) method, a clustering technique, to multivariate data sets for regional lithological mapping in the Chungju area. The study found that this method was particularly successful in classifying the Bulguksa granite and Kyemyongsan biotite-quartz gneiss, though challenges remained in accurately mapping sedimentary rock units due to similarities between different sediments. Park and Kim (1990) conducted a study on the spectral characteristics of rock samples, including bentonites, from the Ulsan area. The research applied unsupervised classification techniques such as Factor Analysis (FA) and ISODATA to data sets derived from Landsat TM bands. The study concluded that certain band ratios, particularly those involving bands 5 and 7, were most effective in distinguishing bentonites from other rock types.

Kang et al. (1990) aimed to analyze the spectral characteristics of various igneous and sedimentary rocks using reflectance curves obtained from a spectrophotometer. The study found that acidic igneous rocks exhibited higher reflectance, while basic rocks showed broad absorption bands due to Fe ions.

Park and Park (1991) focused on the classification of non-metallic minerals and associated rocks in the Ulsan area using remote sensing data. The study utilized feature enhancement and pattern recognition techniques to classify various geological features, with particular emphasis on kaolinite and bentonite deposits. The research demonstrated that histogram-normalized images of certain Landsat TM bands were most effective in identifying outcrops and mine dumps in the study area. Park and Park (1992) conducted a study to extract features of non-metallic ore deposits and their related geology using remote sensing and airborne radiometric data in the Haenam area. The research focused on the reflectance characteristics of minerals and rocks, finding that non-metallic minerals generally exhibited higher reflectance than surrounding rocks. The study highlighted the effectiveness of certain image processing techniques, such as histogram normalization and principal component analysis, in extracting geological features.

Cho et al. (1992) analyzed the spectral characteristics of metamorphic rocks by examining their spectral reflectance curves. The study found that coarse-grained rocks exhibited strong absorption at specific wavelengths due to water inclusions and the presence of Fe ions.

Kang et al. (2001) measured the reflectance of various geological materials, including granite, andesitic rocks, and sedimentary rocks, in the Ungsang area using a field spectrometer. The study identified specific absorption bands for different rock types and suggested that certain Landsat TM and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) bands were most effective for discriminating outcrops. Kim and Lee (2004) applied Linear Spectral Mixture Analysis (LSMA) to geological thematic mapping in the Mongolian plateau using Landsat 7 ETM+ and ASTER data. The study involved the determination of spectral endmembers corresponding to different geological materials, which were used to produce fraction maps of mineral types in the study area.

Kim et al. (2005b) provided a comprehensive review of hyperspectral remote sensing, covering the principles, data processing techniques, and applications of this technology. The study highlighted the potential of hyperspectral data in geological and mineral exploration due to its ability to detect distinct spectral features of rocks and minerals.

Chi and Lee (2007) examined the spectral reflectance characteristics of pyrophyllite mineralized zones to develop a standard methodology for preprocessing rock samples in remote sensing studies. The research identified specific absorption features associated with pyrophyllite, which were correlated with Landsat TM and ASTER bands.

Shin et al. (2010) described the design and construction of a spectral library tailored to the environmental conditions of the Korean Peninsula. The library includes spectral data for various materials, including rocks, minerals, vegetation, and man-made materials. The study emphasized the importance of a region-specific spectral library for improving the analysis of remote sensing data and assisting in the classification of hyperspectral images.

Aisabokhae and Tampul (2019) used Landsat-8 OLI multispectral data to identify and delineate hydrothermal alteration zones in northwestern Nigeria. The study applied various remote sensing techniques, including band ratios and minimum noise fraction, to highlight different mineralogical features. The research demonstrated the effectiveness of these techniques in identifying areas with potential mineral deposits.

Eom et al. (2019) focused on distinguishing between calcite and dolomite in the Okgye-myeon region using spectral characteristics. The study measured reflectance in both field and laboratory settings, identifying significant differences in absorption wavelengths between calcite and dolomite.

The studies reviewed in this section illustrate the diverse applications of remote sensing in rock and mineral analysis in Korea. From early spectral reflectance studies to advanced applications of hyperspectral remote sensing and DEMs, these studies have contributed significantly to the understanding and exploration of geological resources in Korea and beyond. Remote sensing has proven to be a powerful tool in geological mapping, mineral exploration, and monitoring environmental changes related to mining activities. As technologies continue to advance, the integration of multispectral, hyperspectral, and radar data, along with sophisticated data processing techniques, will further enhance the capability to analyze and manage the Earth's geological resources.

3.3. Landslide

Landslides are among the most destructive natural hazards, posing significant risks to life, property, and infrastructure. In Korea, the frequent occurrence of landslides due to the country's mountainous terrain and seasonal heavy rains necessitates continuous monitoring and advanced prediction techniques. Remote sensing has emerged as a critical tool for detecting, monitoring, and predicting landslides. This section explores the advancements in landslide remote sensing in Korea, highlighting key studies conducted over the years using various remote sensing techniques and methodologies.

The study by Kim and Yu (1989) marked an early effort in recognizing landslide activities in the Bonggye area using isopleth mapping techniques. By creating inventory maps of landslide deposits, the researchers were able to generalize and quantify the areal distribution of landslide deposits in contour form.

Chi et al. (2001) conducted a quantitative analysis of GIS-based landslide prediction models using prediction rate curves. Focusing on the Jangheung area, the study compared joint conditional probability and certainty factor models. The results demonstrated the effectiveness of GIS in enhancing the accuracy of landslide prediction models, which has since become a standard approach in landslide hazard assessment. Chi et al. (2002) further explored the use of GIS in landslide prediction by integrating DEM-based hydrological features such as flow-direction, flow-accumulation, and wetness index into their analysis. They highlighted the discrepancies between DEM-based landslide stability analysis and heuristic prediction models, emphasizing the need for unbiased criteria in landslide hazard assessment.

Park et al. (2003) introduced a fuzzy set-based spatial data fusion scheme to account for the fuzziness of boundaries in environmental phenomena. This method showed improved performance in landslide hazard assessment compared to traditional crisp boundary representation. Park et al. (2005) examined the effects of uncertain spatial data representation on multi-source data fusion for landslide hazard mapping. Their findings demonstrated that advanced data representation techniques, such as fuzzy boundary representation and smoothed kernel density estimation, significantly improved prediction rates.

Park and Kyriakidis (2008) explored the integration of different sources of elevation data, such as spot heights and ASTER-based elevation, using geostatistical methods. Their study in Boeun, Korea, showed that the integration of multiple elevation data sources yielded better prediction performance, underscoring the importance of reliable topographic data in landslide hazard mapping.

Oh et al. (2009) analyzed landslide characteristics in the Inje area using SPOT5 images and GIS. Their study highlighted the significance of satellite imagery in understanding the spatial characteristics of landslides, particularly in areas affected by heavy rainfall and typhoons. Oh (2010) utilized digital aerial photography and ANN for landslide detection and susceptibility mapping. The study demonstrated the potential of combining high-resolution aerial images with machine learning techniques to enhance landslide prediction accuracy. Lee and Lee (2017) used logistic regression (LR) models for susceptibility mapping of Umyeonsan, demonstrating the utility of statistical models in predicting landslide-prone areas.

Mezaal and Pradhan (2018) introduced a data mining-aided automatic landslide detection method using airborne laser scanning data. Their study highlighted the effectiveness of integrating LiDAR data with machine learning algorithms for detecting landslides in densely forested tropical areas. Cho et al. (2018) investigated the use of polarimetric SAR data for landslide detection, particularly focusing on landslides caused by the 2016 Kumamoto earthquake in Japan. Their results indicated that fully polarimetric features could significantly improve landslide detection accuracy.

Lee (2019) provided a comprehensive review of the current and future status of GIS-based landslide susceptibility mapping, analyzing trends over two decades. The review emphasized the growing importance of machine learning models and the need for more extensive study areas to improve the generalizability of landslide prediction models.

Fanos et al. (2019) utilized a hybrid Gaussian mixture-ensemble machine learning model and LiDAR data for rockfall source

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identification, demonstrating the power of combining advanced machine learning algorithms with high-resolution data for accurate landslide detection. Park et al. (2018a) compared different probabilistic models, such as the frequency ratio (FR) and evidential belief functions (EBF), in landslide susceptibility mapping, demonstrating the high accuracy of these models in different regions.

Lee and Oh (2019) analyzed landslide susceptibility in Pyeongchang using the weight of evidence, evidence belief function, and ANN models within a GIS framework, based on data from 3,955 landslide occurrences caused by heavy rainfall during Typhoon Ewiniar in 2006. Park and Kim (2020) assessed the efficacy of various models, including the frequency ratio, statistical index, weight of evidence, certainty factor, and index of entropy, in landslide susceptibility mapping. Their findings highlighted the superior performance of the FR model in predicting landslides.

Shin et al. (2020) explored the use of drones for disaster damage investigation in mountainous terrain, demonstrating the potential of drones equipped with real-time kinematic sensors and 3D flight mapping for accurate damage assessment. Jung and Lee (2022) utilized Sentinel-1 InSAR coherence images to monitor mining activity and related landslides in the Fushun West Open-pit Mine in China. Their study underscored the importance of continuous monitoring of mining-induced landslides using advanced InSAR coherence techniques.

Gong et al. (2022) applied deep neural networks and convolutional neural networks (CNN) for landslide susceptibility mapping in Gangwon-do. Their study showed that CNN models outperformed traditional pixel-based models, highlighting the potential of deep learning techniques in enhancing landslide prediction accuracy.

The advancements in landslide remote sensing in Korea demonstrate the growing sophistication of methods and technologies used in landslide detection, monitoring, and prediction. From early mapping techniques to the integration of GIS, machine learning, and SAR data, these studies have significantly contributed to improving landslide hazard assessment in Korea. As technology continues to evolve, the application of deep learning, drones, and other innovative approaches will likely play an increasingly important role in landslide remote sensing, helping to mitigate the risks associated with this natural hazard.

3.4. Volcano

Monitoring volcanic activity in Korea, particularly at significant sites like Baekdusan, is crucial due to the potential hazards associated with volcanic eruptions. This section reviews research published in the KJRS, focusing on studies related to volcanic monitoring using SAR, optical sensors, and Global Navigation Satellite System (GNSS).

3.4.1 Vocanic Deformation

Kim and Won (2005) focused on the Baekdusan stratovolcano, where a series of micro-seismic events and gaseous emissions were reported in the 1990s. By applying the two-pass Differential InSAR (DInSAR) technique using ERS and Japanese Earth Resources Satellite 1 (JERS-1) SAR datasets, the authors detected slow upward deformation of the volcano. The study estimated a mean inflation rate of approximately 3 mm per year from 1992 to 1998, suggesting ongoing magma accumulation beneath the volcano.

Lu et al. (2005) highlighted the application of InSAR to study Alaska's volcanoes, using data from European Remote Sensing (ERS) satellite, Radarsat, and JERS-1. The study demonstrated InSAR's capability to measure ground surface deformation with sub-centimeter precision, providing valuable insights into volcanic activities in Alaska. Kim et al. (2013) monitored the surface deformation of Augustine volcano, Alaska, using Global Positioning System (GPS) data collected before and after the 2006 eruption. The study revealed significant inflation and deflation patterns around the crater, indicating the potential of GPS measurements in predicting volcanic activity.

Cho et al. (2013b). introduced the Temporarily Coherence Point InSAR (TCPInSAR) technique for monitoring volcanic activity in forested areas. The study successfully detected spatial deformation at Augustine volcano, Alaska, using TCPInSAR and Small Baseline Subset (SBAS) techniques, highlighting the effectiveness of multi-temporal InSAR in volcanic regions. Lee et al. (2017) employed multi-temporal InSAR to monitor ground deformation at Sinabung volcano, Indonesia. The study revealed significant inflation and deflation patterns, indicating magma accumulation and withdrawal, and demonstrated the effectiveness of InSAR for long-term volcanic monitoring.

Lee et al. (2018a) applied a refined SBAS algorithm to monitor surface deformation in the Long Valley Caldera. The research highlighted the algorithm's effectiveness in minimizing unwrapping errors and provided detailed insights into the deformation patterns in the region. Jo et al. (2018) utilized SAR interferometry to monitor surface deformation at Kīlauea volcano, Hawaii, during recent eruptive activities. The research demonstrated significant subsidence at the summit, indicating ongoing magma withdrawal and the potential for continued volcanic activity. Song et al. (2018) examined recent volcanic activities at Sierra Negra volcano in the Galapagos Islands using Sentinel-1 SAR data. The study applied Persistent Scatterer InSAR (PSInSAR) and estimated magma chamber depth and expansion, providing insights into the volcano's behavior prior to the 2018 eruption.

Hong et al. (2018) reviewed the use of space-based remote sensing for monitoring Mt. Baekdu, a stratovolcano located on the border between China and North Korea. The paper highlighted various remote sensing techniques, particularly radar interferometry, for observing surface displacement and volcanic activity. The review also discussed the challenges of monitoring this remote and politically sensitive region and underscored the importance of international collaboration in volcano monitoring.

Hong et al. (2019) utilized ALOS-2 PALSAR-2 data to map precise two-dimensional surface deformation at Kilauea volcano, Hawaii, from 2015 to 2017. By applying InSAR and Multiple Aperture SAR Interferometry (MAI) techniques, the researchers identified significant surface deformation, indicating increased volcanic activity. The study demonstrated the ability of SAR interferometry to provide detailed and accurate measurements of volcanic deformation.

The use of remote sensing for monitoring volcanic deformation represents a significant advancement in geological research in Korea. The technologies discussed in this section have not only deepened the scientific understanding of volcanic processes but have also provided essential tools for safeguarding populations and infrastructure from the potential impacts of volcanic activity. As these technologies continue to advance, they will remain at the forefront of efforts to monitor and understand volcanic deformation, thereby contributing to greater resilience against volcanic hazards.

3.4.2. Volcanic Features

Cho et al. (2013a) analyzed the characteristics of Merapi volcano's eruptions over 18 years using Landsat images. By performing supervised classification and converting thermal bands to surface temperature, the study identified the extent of pyroclastic flows and observed precursor changes in surface temperature before eruptions. Kim et al. (2014a) utilized Landsat images to monitor snow cover variations caused by volcanic activities at Mt. Villarrica and Mt. Llaima in Chile. The results indicated that changes in snow cover and snow-line elevation were strongly correlated with volcanic activity, suggesting their use as indicators for monitoring volcanic eruptions. Cho et al. (2014) used Landsat 7 ETM+ images and pyroclastic flow inundation models to monitor volcanic activity at Sinabung volcano in Indonesia.

Kim et al. (2014b) detected volcanic ash from the Sakurajima volcano using the Geostationary Ocean Color Imager (GOCI) and analyzed geomagnetic variations associated with the eruption. The research demonstrated the potential of integrating satellite data and geomagnetic analysis for monitoring volcanic activities. Lee et al. (2014) predicted the spread pathway of volcanic ash from the Sakurajima volcano using the HYSPLIT model and GOCI images. The study found a strong correlation between the model's predictions and the observed ash dispersion, supporting the feasibility of using satellite data for volcanic ash forecasting.

Lee and Jang (2014) applied satellite remote sensing data and the HYSPLIT model to monitor volcanic ash from three major eruptions: Chaitén, Eyjafjallajökull, and Shinmoedake volcanoes. The findings demonstrated a good correlation between satellite-detected volcanic ash and model-derived trajectories, validating the use of integrated approaches for volcanic ash monitoring. Lee and Lee (2014) assessed the damage potential of volcanic ash from the 2014 Mt. Ontake eruption using the HYSPLIT model and GOCI satellite images. The research found satisfactory concordance between simulated ash dispersion and satellite-detected areas, highlighting the importance of predicting ash dispersion to mitigate volcanic hazards. Choi et al. (2017) used COMS and Landsat-8 satellite imagery to analyze the diffusion of volcanic ash from the Sakurajima volcano. The research provided detailed information on ash height and diffusion patterns, demonstrating the advantages of using multiple satellite platforms for volcanic ash monitoring.

Kim and Jung (2017) analyzed the relationship between snow cover changes and volcanic activity at Villarrica and Llaima volcanoes in Chile using Landsat images. The research found a strong correlation between snow cover variations and volcanic activity, suggesting the use of snowline monitoring as an indirect indicator of volcanic activity. Park and Lee (2018) simulated lahar inundation hazard zones at Baekdu volcano using the LAHARZ model and a 30 m DEM. The results demonstrated the model's utility in mapping hazard zones and estimating the extent of damage, providing valuable insights for disaster prevention and emergency planning.

Lee et al. (2018b) reviewed the use of satellite imagery in researching volcanic and seismic activities, particularly focusing on snow-covered areas in the Southern Volcanic Zone of Chile. The study confirmed that changes in snow cover and snowline elevation could serve as indicators of volcanic activity. Sun et al. (2018) used the Near-Infrared (NIR) channels of the GOCI to detect volcanic ash fall deposits from Mt. Aso's 2016 eruption.

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The research demonstrated the effectiveness of satellite imagery in efficiently mapping volcanic ash deposition, offering a powerful tool for hazard response.

Park et al. (2019) focused on monitoring the ice dynamics of Lake Cheonji, a caldera lake at the summit of Baekdu volcano, using TerraSAR-X satellite imagery. The research analyzed 75 images acquired from 2015 to 2017 to monitor seasonal freezing and thawing patterns. The findings suggested that monitoring the lake's ice cover could serve as an indicator of volcanic activity, as changes in ice dynamics might be linked to geothermal activity beneath the lake. Lee et al. (2022) utilized Landsat images and a modified U-Net regression model to quantify the ice gradient in Cheonji, Baekdu Mountain. By analyzing 83 Landsat images spanning from 1985 to 2020, the researchers monitored ice changes in the caldera lake, which may be associated with volcanic activity.

The use of remote sensing for the study of volcanic features has significantly enriched the field of volcanology in Korea. The technologies discussed in this section have enabled detailed and accurate mapping of volcanic structures, providing critical insights into the evolution and current state of volcanic landscapes. These advancements not only contribute to the scientific understanding of volcanic processes but also play a vital role in informing risk management strategies and protecting communities from the potential impacts of volcanic activity.

3.5. Earthquake

Remote sensing provides critical data that helps in monitoring, assessing, and mitigating the impact of seismic activities. This section reviews the key studies published in the KJRS, focusing on the use of satellite optical imagery, SAR, and other remote sensing technologies for earthquake monitoring and analysis.

3.5.1. Earthquake Deformation

Baek and Jung (2018) conducted a study on the surface deformation caused by the 2016 Kumamoto earthquakes using SAR interferometry. They applied ionospheric corrections to multiple-aperture SAR data to accurately measure along-track surface deformation. The results showed significant improvements in detecting fault movements after applying these corrections, contributing to a better understanding of the earthquake's impact on fault structures.

Krishnan and Kim (2018) used PSInSAR techniques to detect land subsidence in the Kathmandu Basin, primarily caused by excessive groundwater withdrawal and crustal displacement due to the 2015 Gorkha earthquake. Achmad and Lee (2021) analyzed the surface deformation caused by the 2020 Mw 6.4 earthquake in Petrinja, Croatia, using Sentinel-1 SAR data. The study applied the Stanford Method for Persistent Scatterers (StaMPS) to generate a deformation map, correcting for errors such as atmospheric and topographic noise. The results showed that the earthquake was dominated by strike-slip faulting, with significant surface displacement.

Fadhillah and Lee (2021) conducted an in-depth analysis of the surface deformation caused by the 2017 Pohang earthquake in South Korea. Using SAR data from multiple satellites with different wavelengths (ALOS-2, COSMO-SkyMed, and Sentinel-1), the study employed the Okada model to estimate the fault parameters and surface deformation. The results provided a detailed model of the fault geometry and helped in understanding the seismic activity responsible for the earthquake. The study highlighted the importance of using multi-frequency InSAR data to achieve a more accurate deformation model.

Lee et al. (2024) analyzed the displacement caused by the 2017 Pohang earthquake at Yeongilman Port and surrounding areas using time-series SAR interferometry with Sentinel-1 data. The study measured displacements over several years, capturing both co-seismic and post-seismic movements. It found that construction activities contributed to significant displacements in certain parts of the port, while the earthquake-induced displacements were generally moderate. The study highlighted the importance of continuous monitoring in understanding the long-term impacts of earthquakes on critical infrastructure like ports.

Kim et al. (2024) examined the horizontal surface displacement caused by the 2024 Noto Peninsula earthquake in Japan using offset tracking techniques. The study aimed to detect and measure surface displacement in regions where ground-based GNSS stations were not available. The analysis revealed significant horizontal displacement, particularly in the northwest region of the peninsula, with displacement values reaching up to 2.9 meters. This research demonstrated the effectiveness of offset tracking in providing critical displacement data in areas lacking ground measurement infrastructure.

The application of remote sensing in the study of earthquake deformation represents a major advancement in the field of seismology and tectonics. The technologies discussed in this section have significantly improved the ability to monitor, analyze, and understand the complex processes underlying earthquake activity. These advancements are not only crucial for advancing scientific knowledge but also for developing practical applications in earthquake preparedness, risk reduction, and public safety.

3.5.2. Earthquake Features

Son and Ryu (2012) investigated the impact of the Great East Japan Earthquake of March 11, 2011, using ocean color data from GOCI. The research focused on monitoring changes in chlorophyll concentration and reflectance in the water after the earthquake and tsunami. The study found that these parameters increased significantly along the Sendai coast immediately after the earthquake, indicating that the tsunami disturbed the water column and affected marine environments. The ocean environment returned to its pre-earthquake condition within two months.

Jo et al. (2017) aimed to analyze the relationship between geological lineaments and earthquake epicenters in the Geochang region, South Korea. Using Landsat 8 imagery and DEM data, lineaments were identified and analyzed through hotspot analysis. The study found a significant correlation between high-density lineament areas and earthquake epicenters, suggesting that lineament analysis can be useful in identifying potential seismic zones.

Cho et al. (2018) investigated the use of fully polarimetric SAR data for detecting landslides triggered by the 2016 Kumamoto earthquake in Japan. The study utilized ALOS-2 PALSAR-2 data and applied adaptive boosting algorithms to classify landslide areas. The results indicated that fully polarimetric SAR data significantly improved the detection of landslides with reduced false alarms compared to single-polarization SAR data.

Lee et al. (2018b) provided a comprehensive overview of the use of satellite imagery in researching earthquakes and volcanic eruptions. The study discussed the advantages and disadvantages of different types of satellite imagery, including optical, thermal, and SAR. The research emphasized the importance of satellite data in monitoring seismic and volcanic activities, offering methods to effectively respond to such natural disasters.

Sohn et al. (2018) examined ionospheric disturbances caused by earthquakes with magnitudes of 5.0 or greater in Korea. The study detected coseismic ionospheric disturbances using GPS data following significant seismic events, including the 2016 Gyeongju earthquake and the 2017 Pohang earthquake. The findings showed that the timing and intensity of ionospheric disturbances varied based on factors such as earthquake depth and the geometry between the GPS stations, satellites, and the epicenter.

Han and Kim (2019) produced a seismic vulnerability map of Gyeongju, the site of the 2016 earthquake, using a GIS and Analytic Hierarchy Process (AHP). The map was created by integrating various indicators related to geotechnical, physical, social, and structural factors. The study classified the area into zones of varying seismic vulnerability and provided valuable information for disaster management and urban planning. Han and Kim (2020) assessed the seismic vulnerability of buildings in Gyeongju using machine learning techniques. The researchers used Random Forest (RF) and Support Vector Machine (SVM) models to predict building vulnerability based on geotechnical and structural factors. The study demonstrated high prediction accuracy, which was used to generate a seismic vulnerability map that identified high-risk areas within the city. Han and Kim (2021) aimed to cross-validate the seismic vulnerability assessment model developed for Gyeongju by applying it to the Pohang region. The study used the same factors and methodology as the original model but tested it on a different dataset related to the 2017 Pohang earthquake. The cross-validation showed that the model performed well in predicting seismic vulnerability in Pohang, though with slightly lower accuracy compared to Gyeongju. This research reinforced the model's applicability across different regions within Korea.

Nur and Lee (2021) generated Damage Proxy Maps (DPMs) using Sentinel-1 SAR imagery to assess the impact of the 2016 Gyeongju and 2017 Pohang earthquakes. By comparing pre- and post-event interferometric coherence, the study identified areas with significant damage. The DPMs correlated well with the modified Mercalli intensity scale and provided a valuable tool for assessing earthquake damage in urban areas.

Gwon et al. (2021) provided a comprehensive review of various remote sensing techniques used in the investigation of active faults, which are critical in understanding earthquake hazards. The paper discussed the principles and applications of satellite remote sensing, airborne remote sensing, InSAR, and LiDAR in identifying and analyzing active faults. The review emphasized the importance of selecting appropriate remote sensing techniques based on specific research needs.

The studies reviewed in this section illustrate the extensive application of remote sensing technologies in earthquake research within Korea. The integration of optical sensors and other remote sensing methods has enriched the understanding of earthquake impacts, contributing to more effective disaster management and mitigation strategies. The advancements in remote sensing, as evidenced by the research in the KJRS, have provided essential

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tools for monitoring seismic hazards, assessing vulnerability, and understanding the complex dynamics of earthquakes. As remote sensing technologies continue to evolve, their role in earthquake research and disaster preparedness is expected to grow, offering even greater insights and capabilities for managing seismic risks.

3.6. Gravity

This section presents a chronological overview of the significant contributions to gravity-based remote sensing research in Korea. The studies highlighted in this section span over two decades, reflecting advancements in satellite technology and ground-based observations that have deepened our understanding of Earth's gravity field, its variations, and implications for geodynamic and hydrological processes.

Kim and Roman (2001) focused on improving the extraction of free-air gravity anomalies from ocean satellite altimetry data, particularly over the Barents Sea. The research introduces a method to enhance the resolution of gravity field models by integrating high-frequency components from ERS-1 satellite altimetry. The study provides a foundational approach to refining gravity anomalies, which is crucial for understanding geological features beneath the ocean surface.

Kim and Lee (2002) addressed the challenges of processing spherical spatial data, particularly the distortions that occur during mathematical transformations like the Fourier Transform. This study presents a method to minimize such distortions, especially in polar regions, by using the Lambert Conformal Conic map projection. The improved accuracy in gravity anomaly data processing contributes to more reliable geophysical analyses in challenging environments.

Neumeyer (2005) highlights the use of Superconducting Gravimeters (SGs) in measuring temporal gravity variations and integrating these measurements with satellite data from the GRACE mission. The paper underscores the importance of combining ground-based and satellite observations to enhance the accuracy of gravity measurements and explores prospects for SG applications in global gravity studies. Crossley and Hinderer (2005) expanded on the application of SGs by comparing ground-based gravimeter data with GRACE satellite observations. The research focuses on seasonal hydrology cycles and highlights the effectiveness of SG arrays in detecting microgal-level gravity variations. The study also explores the potential of SGs in monitoring seismic and volcanic activities, offering insights into their use in geodynamic studies.

Shum et al. (2005) reviewed the capabilities of spaceborne gravity sensors like those on the GRACE and GOCE missions. The study discusses the applications of these sensors in mapping continental water storage and detecting geophysical signals. The research emphasizes the potential of these missions to enhance the temporal and spatial resolution of gravity data, thereby improving our understanding of large-scale hydrological and geodynamic processes. Kim et al. (2005a) analyzed magnetic anomalies detected by the CHAMP satellite, with a focus on polar geodynamic variations. The research presents methods to separate crustal and core magnetic components from satellite data, particularly in regions where external magnetic fields complicate the analysis. This work contributes to improving the accuracy of magnetic and gravity field models in polar regions, where unique geophysical challenges are present.

A decade later, Ko et al. (2015) reported on improvements in Earth's gravity field recovery following upgrades to the GRACE satellite's star tracker data processing. By applying tighter filtering and new calibration methods, the study achieves more accurate gravity field maps, which are crucial for precise geophysical measurements. These improvements mark a significant advancement in the ongoing efforts to refine global gravity models.

The chronological progression of these studies highlights the evolution of gravity-based remote sensing research in Korea. From early improvements in satellite altimetry to the integration of advanced ground-based and satellite technologies, these studies have significantly contributed to our understanding of Earth's gravity field. As technology continues to advance, future research will likely build on these foundations, further enhancing our ability to monitor and analyze geophysical processes on a global scale.

4. Conclusions

The review of remote sensing applications in geological studies across Korea demonstrates the profound impact that advanced sensing technologies have had on our understanding of the diverse and complex geologic phenomena. Through the integration of various remote sensing tools—ranging from satellite imagery and spectral analysis to gravity measurements and machine learning models—researchers have significantly enhanced their ability to monitor, analyze, and predict geological events.

The studies reviewed across different sections show that remote sensing has become indispensable in identifying and characterizing geological lineaments, assessing landslide risks, monitoring seismic and volcanic activities, and understanding subsurface properties through gravity studies. These applications have provided valuable insights into geological framework, enabling more informed decision-making in areas such as natural resource management, disaster preparedness, and environmental conservation.

The advancements in remote sensing have not only improved the accuracy and reliability of geological studies but have also opened new avenues for research. For instance, the integration of ground-based observations with satellite data has proven particularly effective in refining our understanding of subsurface processes and their surface manifestations. Additionally, the adoption of machine learning and other advanced computational methods has further pushed the boundaries of what can be achieved in predictive modeling and hazard assessment.

Despite the significant progress made, the review also highlights ongoing challenges, such as the need for continuous data integration across different scales and the refinement of models to accommodate the complexities of the geological landscape. Furthermore, as the effects of climate change become more pronounced, the role of remote sensing in monitoring and mitigating natural hazards will become even more critical.

In conclusion, remote sensing has established itself as a cornerstone of geological research in Korea, providing critical tools for advancing our understanding of the Earth's processes. The continued development and application of these technologies will be essential in addressing future geological challenges and ensuring the safety and sustainability of the region. As remote sensing techniques continue to evolve, they will undoubtedly play an even more vital role in the ongoing exploration and management of geological resources.

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Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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