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Geological Structures in The Formation of The Kendal Plains: Insights from Remote Sensing Imagery

Struktur Geologi pada Satuan Batuan di Dataran Kendal: Bukti Nyata dari Data Citra Inderaan Jauh

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Abstract - Kendal Area in Central Java experiences rapid regional geology development. A wide flat area extending towards the Pantura, approximately 40 km wide and 20 km long, is influenced by the Bodri River. The Kendal basin formation is driven by Java's regional compression tectonics. Major faults show the east-west direction as thrust faults and northeast-southwest direction as strike slip faults correspond to Java's Regional Structures. Active and passive satellite imagery reveals geomorphic features such as deltas, coastal deposits, paleochannels, break slopes as faults zone, and topographic offsets of the area. The drainage pattern varies with deposit types: distributary channels in the north, meandering channels in the middle, and tributary channels in the south. Fusion image of Landsat 8 and National Digital Elevation Model (DEMNAS) produced by Badan Informasi Geospasial Indonesia (BIG) highlight distinct topographical boundaries and slopes. Residual gravity data shows subsurface contrasts, indicating dominant directions related to surface faults. Other supporting data used include magnetic anomaly imagery processed using the Reduce to Pole (RTP) method which are used to position the source of magnetic anomalies directly above their actual subsurface location. The RTP results enable more accurate interpretation of the distribution and depth of subsurface magnetic sources. The magnetic RTP model aligns with imagery, exhibiting east-west, northeast-southwest, and northwest-southeast trends. This structural interpretation is substantiated by field validation, with evidence of fault cliffs, lithologic offset, fault planes, mylonitization, and fault breccias corroborating the findings.

Keywords: Bodri River, gravity, Kendal, landsat 8, Java's regional structures, magnetic anomaly.

Abstrak - *Area Kendal di Jawa Tengah mengalami perkembangan geologi regional yang pesat. Wilayah pedataran yang luas membentang ke arah Pantura, dengan lebar mencapai 40 km dan panjang 20 km, dipengaruhi oleh Sungai Bodri. Pembentukan cekungan Kendal didorong oleh tektonik kompresi regional di Jawa. Sesar utama menunjukkan arah barat-timur sebagai sesar naik dan arah timurlaut-baratdaya sebagai sesar geser, yang sesuai dengan struktur regional Jawa. Citra satelit aktif dan pasif mengungkap fitur geomorfik seperti delta, endapan pesisir, paleochannel, lereng patahan sebagai zona sesar, dan pergeseran topografi di wilayah tersebut. Pola aliran sungai bervariasi sesuai dengan jenis endapan: saluran distributary di utara, saluran berkelok di tengah, dan saluran tributary di selatan. Fusi citra Landsat 8 dan Digital Elevation Model Nasional (DEMNAS) yang dihasilkan oleh Badan Informasi Geospasial Indonesia (BIG) menyoroti batas topografi dan kemiringan lereng yang jelas. Data gravitasi residual menunjukkan kontras bawah permukaan, mengindikasikan arah dominan yang terkait dengan sesar permukaan. Data pendukung lain yang digunakan mencakup citra anomali magnetik yang diolah menggunakan metode Reduksi ke Kutub (RTP) untuk memposisikan sumber anomali magnetik tepat di atas lokasi sebenarnya di bawah permukaan. Hasil RTP memungkinkan interpretasi yang lebih akurat mengenai distribusi dan kedalaman sumber-sumber magnetik di bawah permukaan. Model RTP magnetik selaras dengan citra, menunjukkan kecenderungan timur-barat, timur laut-barat daya, dan barat laut-tenggara. Interpretasi struktural ini didukung oleh validasi lapangan, dengan bukti tebing sesar, pergeseran litologi, bidang sesar, milonitisasi, dan breksi sesar yang menguatkan temuan tersebut.*

Katakunci: *Sungai Bodri, gaya berat, Kendal, landsat 8, struktur regional Jawa, anomali magnetik.*

INTRODUCTION

The region of Kendal, situated in Central Java, has garnered significant attention due to its rapid regional development and evolving geological landscape. The area encompasses a wide flat expanse extending towards the Pantura, with dimensions of approximately 40 km in width and 20 km in length, oriented along the axis of the Bodri River (Astuti *et al.*, 2021). This region has been subject to dynamic geological processes driven by the tectonics of Java's regional compression (Bachri, 2014).

The Kendal flood basin, formed through complex geological interactions, the interplay between tectonic forces, geological structures, and depositional processes has resulted in the accumulation of Quaternary deposits, reshaping the landscape over time (Poejoprajitno *et al*., 2009; Siswanto, 2007). Understanding the factors that have contributed to the formation and evolution of this basin is crucial not only for unraveling the region's geological history but also for implications in various geoscience disciplines, including tectonics, geomorphology, and sedimentology.

To shed light on the complexity geological setting of Kendal, this study employs a multi-faceted approach that combines satellite imagery, geomorphic analysis, and geophysical data interpretation. The integration of these methodologies offers a comprehensive view of the region's landscape evolution, drainage patterns, structural features, and subsurface characteristics (Fossi *et al.,* 2021; Mwaniki, *et al*., 2015). By delineating the geological history of Kendal, this research seeks to contribute valuable insights into the broader understanding of tectonic processes and landscape evolution in similar geological contexts.

In this paper, we present a detailed analysis of the surface geomorphic features, drainage patterns, structural elements, and subsurface patterns observed within the Kendal basin. The study leverages remote sensing data, field observations, and geophysical interpretations to unravel the geological complexities that have shaped the region. The findings presented herein contribute to our understanding of the interplay between tectonic forces, depositional processes, and geomorphic evolution in Kendal, with implications for broader geological research and regional development considerations.

DATA AND METHODOLOGY

The interpretation of structural geology in the Kendal Area of Central Java was facilitated through the integration of remote sensing data and geophysical images of gravity and magnetic anomalies. Landsat 8, a passive satellite, played a pivotal role in this study, serving as a valuable tool for the identification and characterization of lithologic units within the study area. Utilizing a combination of Near-Infrared (NIR) and Shortwave Infrared (SWIR) bands, sensitive to hydroxyl content, the Landsat 8 imagery enabled the delineation of lithological features within this flood basin environment (Mwaniki, *et al*., 2015). To enhance the morphological analysis, Digital Elevation Model of DEMNAS as an active satellite data was employed, allowing for the examination of lineaments, slope variations, topographical offsets, and drainage patterns (Fossi *et al.*, 2021). The fusion of Landsat 8 and DEMNAS data synergistically combined spectral and elevation information, compensating for the differing spatial resolutions of 30 meters and 8 meters, respectively (Figure 1).

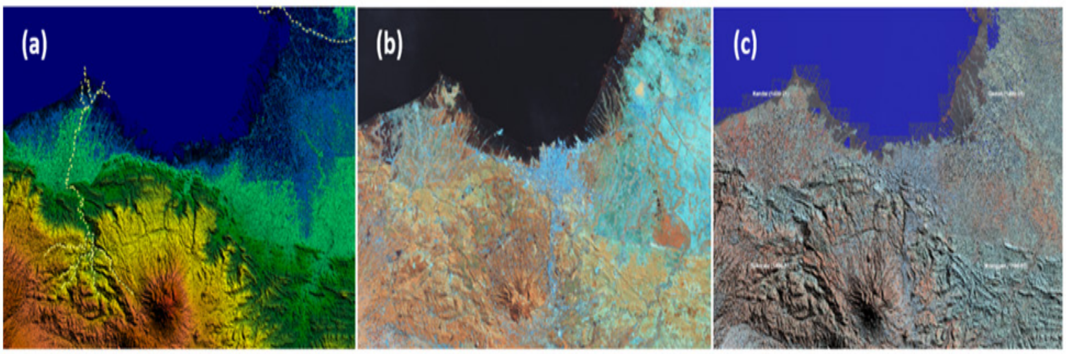

Figure 1. Remote sensing data used in this study. (a) Digital elevation data DEMNAS with color elevation shader, (b) Landsat 8 using combination of NIR and SWIR bands, and (c) Image Fusion of DEMNAS and Landsat 8 provides combination of spectral and elevation features in 8 m spatial resolution.

Complementing this approach, geophysical images depicting gravity and magnetic anomalies were derived from field surveys conducted along multiple traverse lines. These images served as informative companions for interpreting geological structures from a subsurface perspective (Wardhana *et al*., 2014). To validate the robustness of the interpretation outcomes, comprehensive field surveys were conducted. These on-site excursions provided a direct and practical means of corroborating the interpreted geological features. Structural elements such as joints, slicken sides, mylonite occurrences, and brecciation phenomena were meticulously documented and cross-referenced with the remote sensing and geophysical interpretations. Additionally, the orientation of bedding (expressed through the strike and dip) was carefully measured and compared to the subsurface projections. This thorough validation process, grounded in empirical observations, contributed to the enhanced credibility and reliability of the interpreted geological insights within the Kendal Area.

RESULTS AND DISCUSSION

Physiography of Pekalongan-Kendal-Demak

The separation of morphography classes was performed on elevation images by dividing the elevation below 5 meters above sea level (masl) into sub-classes at intervals of 2.5 meters. Subsequently, the elevation range between 10 masl and 50 masl was divided into 3 sub-classes: 10 masl, 25 masl, and 50 masl. Hills with elevations below 500 masl were divided into 4 sub-classes, and finally, for mountainous regions up to 1250 masl, they were divided into 3 sub-classes. This technique was employed to achieve a more refined topographic pattern, particularly for the coastal plain areas along the North Coast (Figure 2).

The physiography of the Kendal Area and other regions along the northern coast of Java (*Pantura*) within an expanded coverage, encompassing the Pekalongan-Kendal-Demak area, based on the analysis of digital elevation model data through the separation of elevation classes with a color shader, exhibits contrasting morphography from south to north (Figure 2). The morphology of hills and mountains is evident on the image map, situated in the southern to central parts (200 masl to 1,250 masl), gradually transitioning into the northern plains, forming alluvial fans (2.5 masl to 100 masl).

The hill-mountain areas represent the Tertiary-Quaternary volcanic belt composed of volcanic rocks such as lava, breccia, and tuff (Bachri, 2014; Thanden *et al.*, 1996). The coastal area of Pekalongan-Demak is characterized by alluvial plains accompanied by fan-shaped morphologies. These areas give rise to several significant deltas, including the Comal River Delta in the Pekalongan Area, the Bodri River Delta in the Kendal Area, and the Wulan River Delta in the Demak Area (Sidarto *et al.*, 2020). The process of rock erosion in the southern region supplies sediments to the northern coast through the main river flow, with the merging of tributary channels in the upper part and the formation of distributary channels in the lower part.

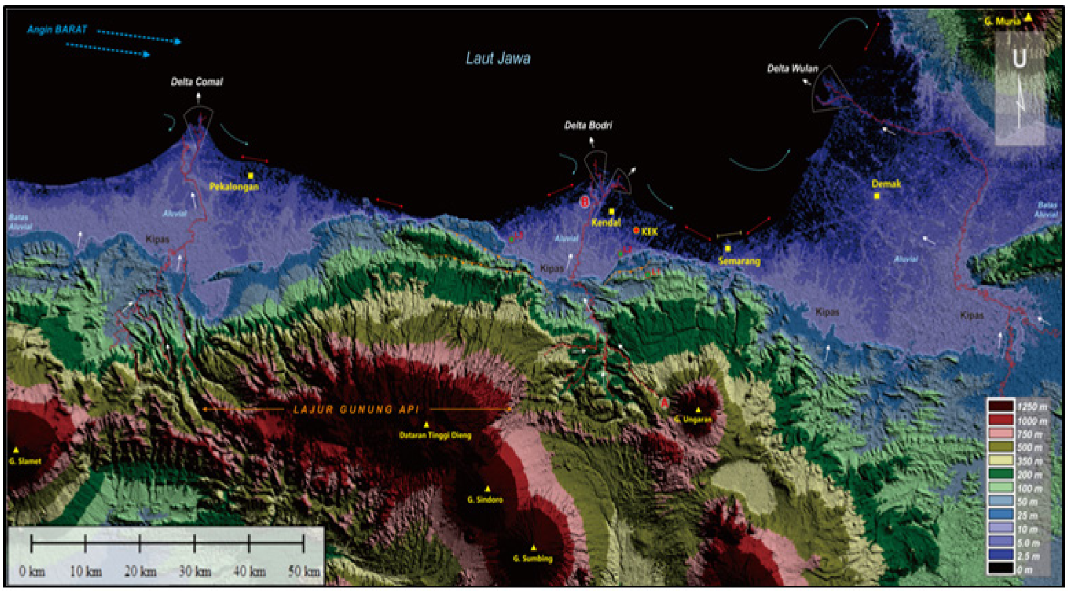

Figure 2. The separation of elevation classes with color shader on DEMNAS data exhibits contrasting morphography from south to north. This technique was employed to achieve a more refined topographic pattern.

The alluvial fan deposit occupies a portion of the Kendal region and extends nearly 20 km from north to south. These deposits manifest as erosional-sedimentary outcomes comprising diverse rock materials originating from the southern region, which emerged due to alterations in sedimentary flow velocity in the lowland terrain of Kendal. Variations in river flow competence and capacity in the mountainous-hilly terrain gave rise to the formation of these deposits, characterized by the amalgamation of tributary flows in the southern Kendal Area. Downstream, the river flow velocity diminishes, carrying solely fine materials that contribute to the formation of coastal swamps and a delta. The formation of a delta at the Bodri River's course gives rise to distributary channels as accommodations for the accelerated deposition within the delta (Sidarto *et al.,* 2020). This area extends up to 2 km towards the Kendal coastline.

Stratigraphy of The Kendal Area

Image Fusion of Landsat 8 and DEMNAS were used to highlight the morpho-structural pattern of the area. The use of band near-infrared and shortwave-infrared with band combination R/G/B:5/6/7 that sensitive to hydroxyl objects (Mwaniki, *et al.*, 2015) in the Kendal flood basin has made this technique versatile to delineate lithological units such as swamp, old river channel, fan deposits, beach deposits, and active river channel. Image enhancement was also carried out to sharpen satellite imagery using Panchromatic Band 8 using Gram-Schmidt Sharpening method. In combination with 8 m resolution of elevation data, several faults were identified from slope class and the changes in drainage patterns. Some topographic offsets typically in river channels were observed as horizontal faults.

The stratigraphy of the Kendal Area is composed of surface deposits and sedimentary rocks ranging from Pliocene to Pleistocene ages. The oldest unit consists of Breccia of the Damar Formation interbedded with Sandstone of the Damar Formation; deposited in terrestrial to transitional environments (Poejoprajitno *et al.*, 2009); Lumbanbatu, 2009). The youngest unit consists of alluvial deposits occupying river plains, swamps, and the coast (Figure 3b). The river deposits comprise gravel, pebbles, sand, and silt with a thickness of 1 - 3 meters (Poejoprajitno *et al.*, 2009). The sand deposits forming the delta are a water-bearing layer with a thickness of over 80 meters. The coastal plain is generally composed of clay and sand with a thickness reaching 50 meters or more (Thanden *et al.*, 1996). These alluvial deposits are widespread, covering most of the map sheet.

Kendal is one of the alluvial plains on the northern coast of Java. It is primarily formed by Quaternary-aged fan deposits and fluvial sediments. Its southern part is bounded by the break-slope of the Damar Formation hills. This boundary coincides with changes in lithology and the location of a west-east trending fault. Based on shallow borehole data interpretation, this plain serves as a sediment deposition basin for both volcanic hills and Tertiary sediments from the south (Poejoprajitno *et al.*, 2009; Lumbanbatu, 2009). Its stratigraphy consists of surface deposits and rocks ranging from Upper Tertiary to Quaternary in age. The oldest rocks consist of sedimentary rocks from the Damar Formation and the Sandstone Member of the Damar Formation, which are derived from the erosion of older volcanic materials.

Geological Structures of The Kendal Area

Pliocene-Pleistocene tectonics led to uplift in this area, subsequently forming the Kendal plain in the northern part (Bachri, 2014). The process of eroding volcanic rocks in the southern area beyond the map sheet contributed sediment input to the Kendal Plain area, characterized by the formation of an alluvial fan with its main channel being the Bodri River. This channel flows and develops into several deltas on the Kendal Coast, namely: Damar Delta, Blukar Delta, Bodri Delta, and Cangkring Delta. The development of swamp and coastal deposits in this area showcases active coastal dynamics marked by the intensive changes in coastline, deltas, and floodplains (*rob*).

The Kendal Plain is controlled by faults that are segments of the Baribis Fault (Wardhana *et al*., 2014). The thrust fault has made the northern block positioned lower, leading to a break-slope that decreases the river gradient and causes seawater to encroach onto the plain. These conditions provide a deposition environment in the form of fans, river deposits, marshes, and coastal areas that develop over the long-term period.

A west-east trending thrust fault separates the distribution of older rocks from Quaternary deposits, and this fault is further intersected by an east-northeast to west-southwest trending strike-slip faults. Those faults have caused the formation of a northern sedimentary basin (fluvio-deltaic basin) that experienced subsidence; subsequently, it was filled with Quaternary deposits consisting of fluviatile and deltaic deposits (Figure 3).

The gravity anomaly map of the Kendal region reveals distinctive variations in gravitational field strength across the area. Notably, there is a strong positive gravity anomaly in the southern area indicating the volcanic features, which indicates the presence of denser rock formations beneath the surface (Wardhana *et al.*, 2014). On the northern part of the map, the Kendal flood basin indicated by medium anomaly which coincidence with the flatland area in the surface bounded by contrast anomaly of east-west trend. The lineament patterns between the anomaly suggests the potential existence of faults with east-west, northwest-southeast, and northeast-southwest trends. The negative gravity anomaly observed towards the central part of the region hints at the presence of less-dense lithologies as well as the possibility of fold mechanism which indicated by the orientation of the object in east-west trend. This information aligns with the hypothesis that this area is controlled by the north-south compression tectonic (Figure 4a).

Based on surface lineament interpretation from Landsat 8 imagery and DEMNAS, along with subsurface lineaments from gravity anomalies and magnetic imagery, several geological structure patterns are identified in the Kendal area: an east-west trending geological structure, which is the main structure with a thrust fault mechanism; a northwest-southeast trending structure with a strike-slip fault mechanism that intersects the main fault; and other northeast-southwest trending strike-slip faults that formed after the thrust fault.

The magnetic anomaly map of the same Kendal region shows a similar pattern. The substantial positive magnetic anomaly coincides with the previously mentioned positive gravity anomaly. This alignment indicates the possible occurrence of magnetic rock formations and the presence of faults with similar trends within the area. Conversely, a negative magnetic anomaly located on the Kendal plain could indicate an area with non-magnetic objects such as Quaternary flood basin deposits. Variations in these magnetic anomaly patterns reflect underlying rock composition and structural trends that correlate with interpretation at the surface with remote sensing data (Figure 4b).

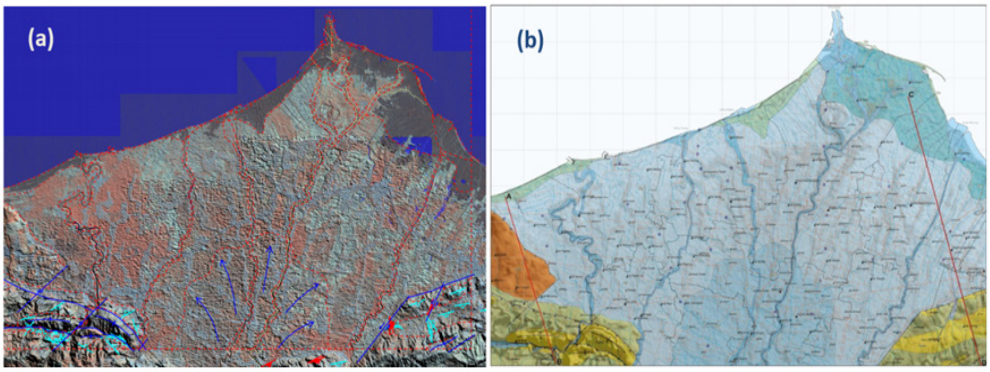

Figure 3. (a) Fusion images of Landsat 8 and DEMNAS of the Kendal Area show morphological patterns such as fan and break-slope as fault lines. The red line is an interpretation of lithological boundaries; blue lines are for faults, blue lines with arrows are fan directions; the cyan symbol is strike/dip of bedding; and the red symbol is strike/dip fault plane (measured from field survey). (b) Geological map of the Kendal Area derived from remote sensing analysis and field survey validation; red lines with letter A-B and C-D in picture 'b' are geological cross sections.

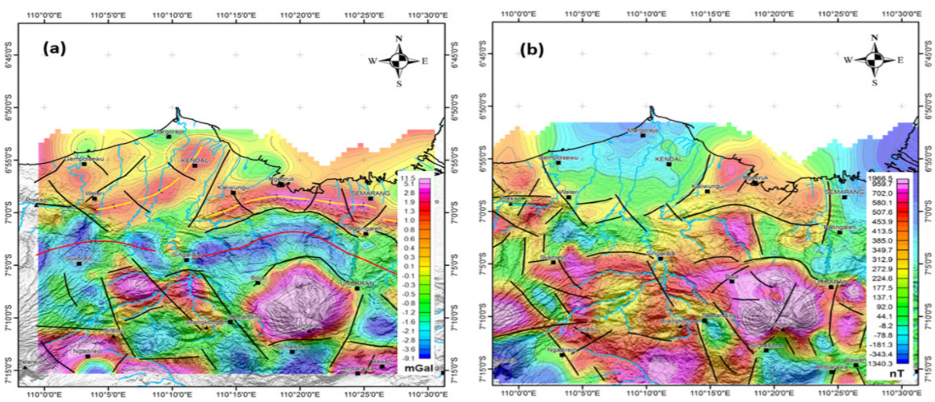

Figure 4. Geophysical images of gravity and magnetic anomalies depict subsurface structural patterns that correlate in position and orientation with surface geological structures as analyzed from Landsat and DEMNAS data. Thrust faults in east-west direction and strike-slip faults in the direction of northeast-southwest and northwest-southeast in line with Java's Regional Structural Pattern.

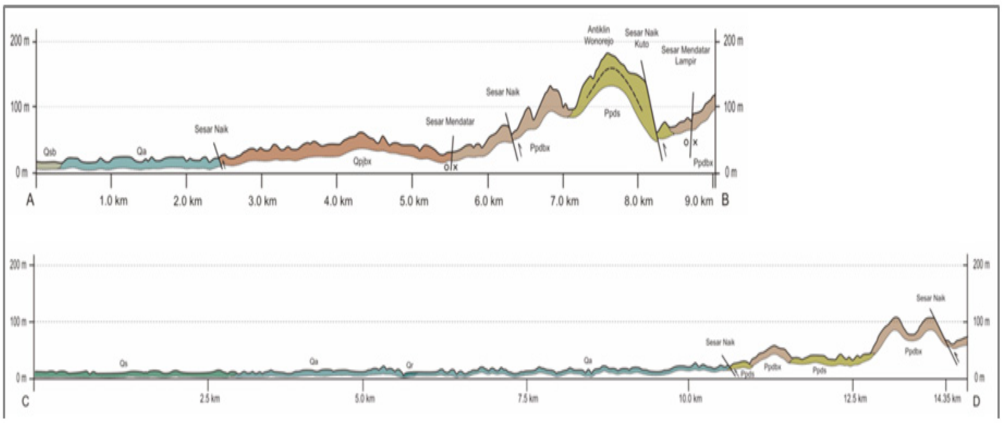

Figure 5. The cross-section from the geological map in Figure 3b; shows the existence of the geological structures caused by north-south tectonic compression in the Kendal Area, resulting in the formation of the east-west trending folds and thrust faults which were cut by the next-order strike-slip faults of northeast-southwest trending.

Based on the field survey, the interpretation of geological structures of the Kendal Area was validated through the observation and findings of the strike-dip beddings, joints, fault scarps, mylonitisation, fault breccia as well as slicken sides along the fault zone in the southern Kendal Area. This validated the presence of the east-west folds and thrust faults which separate the Kendal Plain from hilly terrain as tectonic control in the generation of flood basin. The geological cross-section shows the configuration of folds, thrust faults, and strike-slip faults on the southern part of the Kendal Area caused by north-south tectonic compression (Figure 5).

CONCLUSIONS

The use of remote sensing imagery can help strengthen geological surveys in the Kendal Area, especially the use of the near infrared - shortwave bands in coastal and floodplain environments which can distinguish variations in surface objects due to their clay and moisture content. The combination with medium resolution elevation data can highlight geological structure objects remotely. The integration of gravity maps and magnetic anomalies provides a comprehensive picture of the complexity of the geological structure of the Kendal Area and its surroundings. Gravity imagery maps and magnetic anomalies assist in identifying areas with subsurface structural patterns as shown on the surface by Landsat and DEMNAS. Ground-based geological surveys have validated this hypothesis and advanced understanding of the region's geological structures.

The geological structure and patterns successfully identified in the Kendal area through this study are: an east-west trending geological structure, which is the main structure with a thrust fault mechanism; a northwest-southeast trending structure with a strike-slip fault mechanism that intersects the main fault; and other northeast-southwest trending strike-slip faults that formed after the thrust fault. These geological structures represent new findings that were not previously included in published geological maps, thus this result can be used as an update for previous geological maps.

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