Jurnal Geologi dan Sumberdaya Mineral Vol. 26 No. 3 Agustus 2025 hal. 213-226

Geo-Science

Jurnal Geologi dan Sumberdaya Mineral
Journal of Geology and Mineral Resources
Center for Geological Survey, Geological Agency, Ministry of Energy and Mineral Resources
Journal homepage: http://jgsm.geologi.esdm.go.id
ISSN 0853 - 9634, e-ISSN 2549 - 4759

Clay Mineral Characteristics of the Damar Formation in the Southern Part of the Coastal Area of Semarang and Kendal, Central Java

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Submit: 19 June 2025, Revised: 6 August 2025, Approved: 22 August 2025, Online: 31 August 2025
DOI: 10.33332/jgsm.geologi.v26i3.997

Abstract- The study area is located in the southern part of the Coastal area of Semarang and Kendal, Central Java. The fine-grained sedimentary rocks of Damar Formation comprise tuffaceous mudstones, volcanic breccias, sandstones, tuffs and conglomerates; with occasional lava deposits and volcanic materials within alluvial fan deposits.

The purpose of this study is to provide data on the characteristics of fine-grained sedimentary rocks of the Damar Formation including physical characteristics, diagenesis processes, and their implications for the history of rock accumulation. Based on Scanning Electron Microscope (SEM) analysis of four claystone samples from the Damar Formation consist of illite ($K_{1-1.5}Al_4(Si_{7-6.5}Al_{1-1.5}O_{20})(OH)_4$, mixed illite ($K_{1-1.5}Al_4(Si_{7-6.5}Al_{1-1.5}O_{20})(OH)_4$ - smectite $(1/2Ca)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}).nH_2O$ and kaolinite ($Al_4(Si_4O_{10})(OH)_8$. Other minerals include silica or quartz fractions and feldspar. Kaolinite is the most prominent clay mineral identified in all claystone samples analysed, although the clay textures seem to be irregular shapes of Damar Formation has undergone a diagenetic process within a mesodiagenetic level indicating sediment burial at depths of 2,500–4,000 m by temperature ranging from 80° to 120°C.

Keywords: Damar Formation, SEM, diagenesis, clay mineral, illite.

Abstrak- *Area studi terletak di bagian selatan pantai Semarang dan Kendal, Jawa Tengah. Sedimen berbutir halus dari Formasi Damar terdiri dari batulumpur tufaan, breksi vulkanik, batupasir, tuf, dan konglomerat, dengan setempat deposit lava dan material volkanik dengan endapan kipas aluvial.*

Tujuan dari studi ini adalah untuk menyediakan data terkait karakteristik dari batuan sedimen berbutir halus dari formasi Damar termasuk karakter fisik, proses diagenesis, dan implikasinya untuk sejarah akumulasi batuan. Berdasarakan Mikroskop Scanning Elektron (SEM) analisis dari 4 (empat) percontoh batulempung Formasi Damar terdiri dari illit ($K_{1-1.5}Al_4(Si_{7-6.5}Al_{1-1.5}O_{20})(OH)_4$, *campuran illit* ($K_{1-1.5}Al_4(Si_{7-6.5}Al_{1-1.5}O_{20})(OH)_4$ - *smektit* $(1/2Ca)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}).nH_2O$ *dan kaolinit* ($Al_4(Si_4O_{10})(OH)_8$. *Mineral lainnya adalah silika atau kuarsa berupa fraksi, felspar. Mineral lempung kaolinit merupakan mineral lempung yang paling menonjol dari analisis batu lempung, meskipun tekstur lempungnya berbentuk kurang teratur yang menandakan proses diagenesis pada level mesodiagenesis yang pernah terpendam sampai 2500 – 4000 meter dengan temperatur berkisar* $80^o – 120^o$.

Kata kunci: Formasi Damar, SEM, diagenesis, mineral lempung, illit.

INTRODUCTION

Central Java is the third most densely populated province in Indonesia, with a population of approximately 37 million people, with an average density of around 1,000 inhabitants per square kilometre. About 60% of this population is concentrated in the northern lowland areas, which are geospatially advantageous due to their flat topography and proximity to the coast. Nevertheless, these low-lying regions are highly susceptible to land subsidence, particularly in areas dominated by the accumulation of alluvial and coastal sediments (Fig. 1). This geohazard has significant implications for urban development, infrastructure stability, agricultural productivity, and the increasing risk of seawater intrusion along the coastal boundaries.

Land subsidence refers to the gradual sinking or settlement of the Earth's surface, resulting in a decrease in land elevation. It is a geodynamic phenomenon driven by both geological processes and human-induced activities. Previous studies have identified several anthropogenic drivers of land subsidence, including excessive groundwater extraction, underground mining, peatland drainage, and natural gas exploitation (Andreas *et al.*, 2020; Ackin, 2021; Sarah *et al.*, 2021; Ma *et al.*, 2022; Nozadkhalil *et al.*, 2023; Sahu & Rawat, 2023). However, it is hypothesized that land subsidence in the northern parts of the Central Java, particularly in Kendal and Semarang areas, are not solely attributable to human activities. Geological factors are also contribute substantially. Specifically, the gradual surface deformation may be related to the mechanical reaction of Quaternary alluvial deposits and the underlying sedimentary formations, as suggested by Rau *et al.* (2020) and Buffardi & Ruberti (2023).

Based on the geological setting, the Damar Formation, underlying the Quaternary alluvium in northern Central Java, warrants detailed examination. The upper part of this formation comprises tuffaceous mudstone, sandstone, claystone, limestone, and volcaniclastic materials. According to Bjorlykke (1998), the presence of clay minerals and clastic sheet silicates can significantly influence the physical and chemical properties of sedimentary rocks such as sandstone and shale. These properties are shaped by the nature of the source rocks, weathering and erosion conditions, sediment transport mechanisms, and depositional environments. Although Semarang and Kendal share a common regional geological framework, their sedimentary basins display distinct subsidence patterns and depositional histories. Furthermore, clay diagenesis, which controls compaction and consolidation processes, is controlled by a variety of geological and geochemical factors.

This study examines the characteristics of fine-grained sedimentary rocks of the Damar Formation, emphasizing their physical properties, diagenetic processes, and implications for sediment accumulation history. The finding aims to clarify the geological contributions to land subsidence in the region and provide new insights into the basin evolution of northern Central Java.

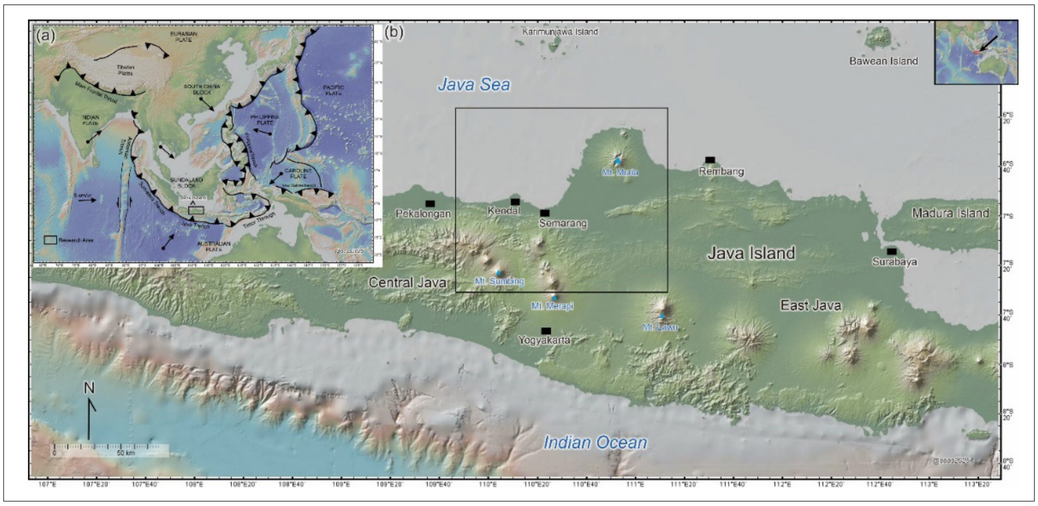


Figure 1. Location of the study area. (a) Plate tectonic setting of southeast Asia, which are plate boundaries, major structures, and plate motion direction follow Metcalfe (2011). (b) Location of Kendal – Semarang in northern coastal area Java Island whereas southeast margin of Sundaland Block as shown a black rectangle in (a). Figure base made with GeoMapApp (www.geomapapp.org). CC BY (*Ryan et al.*, *2009*)

METODOLOGY AND ANALYSIS

Samples were analysed using Scanning Electron Microscope (SEM) to examine the surface morphology and microstructural features of the mineral phases (Trzciński & Wójcik, 2019; Rigby & Himona, 2024). Prior to analysis, the samples were cut into 20 mm^3 pieces and carefully cleaned using an air spray to remove surface dust and contaminants. The specimens were then mounted onto a copper using conductive glue containing metal powder. Subsequently, each sample was coated with a thin layer of gold by vacuum evaporation through electrolytic deposition. The SEM observations allowed for detailed characteristics and physical properties of the samples in terms of 3D grain relationships, clay matrix, cementation, texture and structure, mineral types and configurations, as well as the orientation and size of cavities down to the micron scale.

GEOLOGICAL SETTING

The study area can be divided into hilly morphology in the southern and coastal lowland in the northern part. The coastal lowland is covered by alluvial deposits, lying at an altitude of less than 1 meter up to 8 m above sea level, with slope between 0^o to 5^o. Several rivers originate from the hilly area in the south, including Damar, Klampi Blorong, and Bodri Rivers. The hilly morphology reaches elevations of up to 112 m above sea level, underlain by the Lower Pliocene - Pleistocene of Damar Formation (Qtd).

Stratigraphy of the study area is described as follows:

Alluvium

The coastal, river, and lake alluvium deposits consists of clay, silt and sand and a mixture of them reaches a thickness of 50 m or more. River and lake deposits consist of gravel, pebbles, sand and silt with a thickness of 1 - 3 m. The boulders are composed of andesite, claystone and a little sandstone.

Gajah Mungkur Volcanic Rock

The rock is andesite lava, blackish gray in color, fine-grained, holocrystalline, the composition consists of feldspar, hornblende and augite, is hard and compact. The outcrop locally shows a sheeting joint structure.

Kaligesik Volcanic Rocks (Qpk)

Kaligesik Volcanic Rocks are basaltic lava, blackish gray in color, smooth, mineral composition consists of feldspar, olivine and augite, very hard.

Jongkong Formation

Andesite hornblende augite breccia and lava flows, previously called Old Ungaran volcanic rocks. Andesite breccia is blackish brown, components measuring 1 - 50 cm, angular - semi-rounded with a tuffaceous base mass, medium porosity, compact and hard. Lava flows are dark gray, fine-grained, and locally show vesicular structures (hollow).

Damar Formation

The Damar Formation consists of tuffaceous mudstones, volcanic breccias, sandstones, tuffs and conglomerates; locally includes lava the alluvium fan is composed of volcanic material (Fig.2). Furthermore, the morphology of its formation is generally undulating with a range of slopes from gently sloping to moderately steep (Jamal *et al.*, 2022; Moechtar and Mulyana, 2010).

The rocks consist of tuffaceous sandstone, conglomerate, and volcanic breccia. Tuffaceous sandstone is brownish yellow with fine - coarse grains, composition consists of mafic minerals, feldspar, and quartz with a tuffaceous base mass, medium porosity, hard. Conglomerate is brownish yellow to blackish, components consist of andesite, basalt, pumice, 0.5 - 5 cm, slightly rounded to well rounded, rather brittle. Volcanic breccia may be deposited as lava, blackish gray in color, components consist of andesite and basalt, 1 - 20 cm, angular - slightly rounded, rather hard.

Kaligetas Formation

The rocks consist of breccia and lava with fine to coarse lava and tuff inserts, locally in the lower part is claystone containing mollusca and tuffaceous sandstone. Breccia and lava are blackish brown in color, with components in the form of andesite, basalt, pumice with a tuff base mass, components are generally angular - slightly rounded, medium to high porosity, breccia is hard and compact, while lava is rather brittle. Lava is black-gray, hard and compact. Tufa is whitish yellow, fine - coarse, high porosity, brittle. Claystone, green, low porosity, rather hard when dry and easily destroyed when wet. Tuff sandstone, yellowish brown, fine – medium, medium porosity, rather hard.

Kalibeng Formation

The rocks consist of marl, tuffaceous sandstone and limestone. Marl is greenish gray to blackish, the composition consists of clay minerals and carbonate cement, low porosity to watertight, rather hard when dry and easily destroyed when wet. Locally, the marl contains carbonaceous material or organic matter. Tuff sandstone is blackish yellow, fine – coarse grained, medium porosity, rather hard, Limestone is a lens in marl, grayish white, hard and compact.

Kerek Formation

Alternation of claystone, marl, tuffaceous sandstone, conglomerate, volcanic breccia and limestone. Light to dark gray claystone, calcareous, partly interbedded with siltstone or sandstone, containing fossils of foraminiferas, molluscs and colonial corals. Thin layers of conglomerate are found in the claystone in K. Kripik and in the sandstone. Limestone is generally layered, crystalline and sandy, with a total thickness of more than 400 m.

Thanden R.E. *et al.* (1996) stated that the tectonic of the area started at the Early Tertiary, as evidenced by basaltic and andesitic intrusion, followed by uplifting and erosion. The erosion product formed

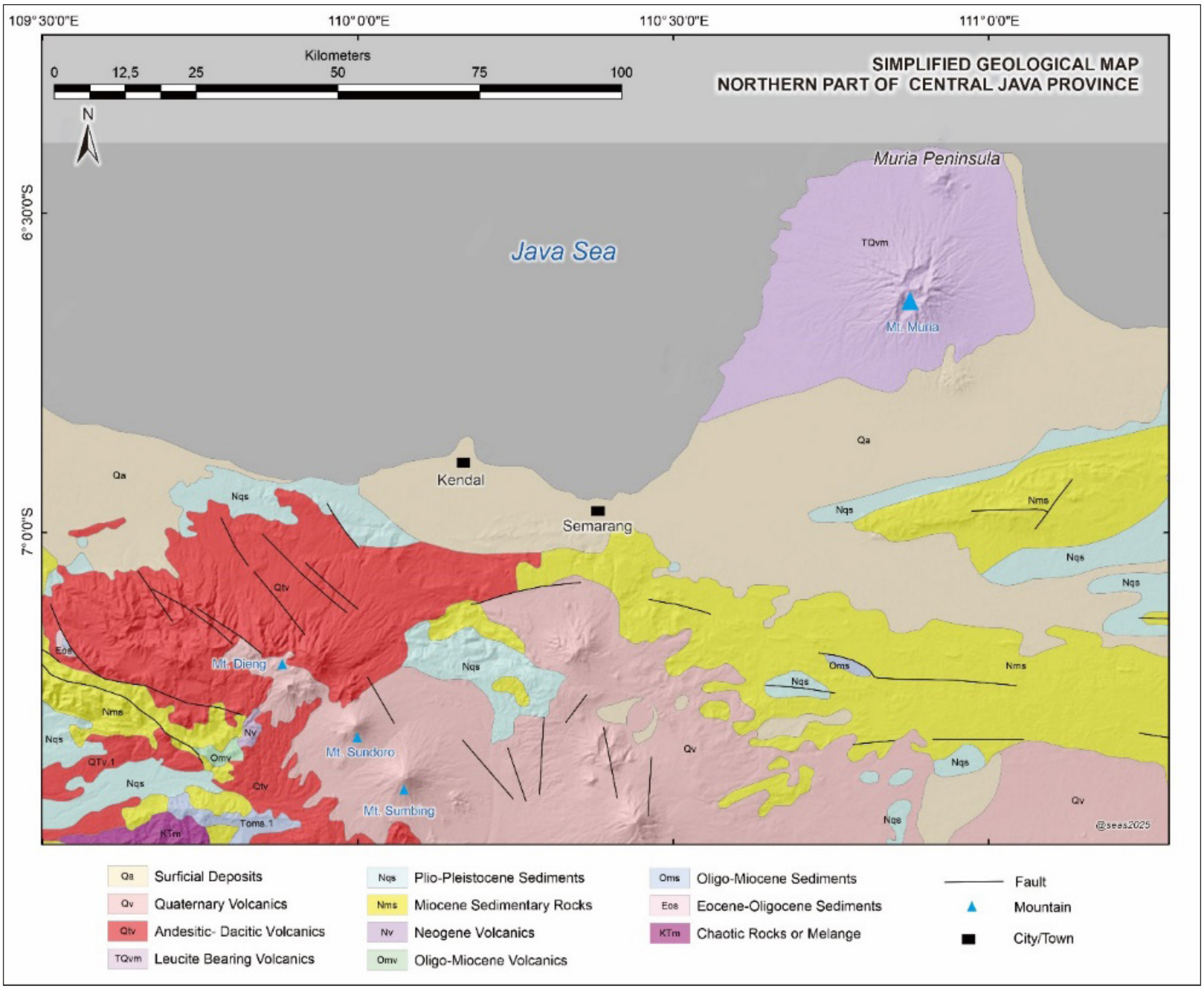


Figure 2. Regional geological map of the northern part of Central Java Province, (Simplified from Ratman *et al.*, 1998)

the turbidites of the Kerek Formation in the neritic environment which is subsequently overlain by the Kalibeng Formation in a bathyal environment and basin filling of the Damar Formation in a transitional to terrestrial environment. The Plio-Pleistocene tectonic reactivation induced Early Tertiary Deformation, producing dominantly East–West (E-W) asymmetrical fold, followed by E-W thrust fault, NE-SW, and NW-SE strike-slip fault, also normal fault. These structural features generated fractures form a weak zone for the rise of young Quaternary volcanic rocks.

STRATIGRAPHY AND SEDIMENTOLOGY OF THE DAMAR FORMATION

The stratigraphy and sedimentology of the Damar Formation consist of three members and each member has a typical characteristic depositional environment from a marine to fluvial (Suyono *et al.*, 2025), as follows:

The lower sequence is characterized by interfingering between breccia and tuffaceous sandstone, typically represents a volcanic deposit within distal facies of the intra-arc basin.

Middle sequence is dominated by intercalation between conglomerate and fluviatile sandstone with green silty–clay lamination, indicating that the area was a transition zone between fluvial and lacustrine environments..

The upper part of the sequence is predominantly of black and green clay which is rich in foraminifera, pollen, and marine mollusc indicating an open marine to transition depositional environment.

Biostratigraphic analysis of greenish and black clay of Upper Damar Formation at Genuk Borehole were conducted based on foraminiferal and palynomorph assemblages. Identifications of foraminifera were done based on Blow (1969), Barker (1960) and Bolli *et al.* (1985), while palynomorph identification was based on Morley (1990, 2000).

Palynological analysis of GNK-4, indicates the first occurrence of *Polvadovellenites vancompei* (*Accacia type, Leguminosae*) and *Moraceae* as lowland vegetations, *Florschuetzia meridionalis* (*Lythraceae*) and *Zonocostites ramonae* (*Rhizophora type, Rhizophoraceae*), the depositional environment is identified as terrestrial close to mangrove.

RESULT

SEM Analysis Results

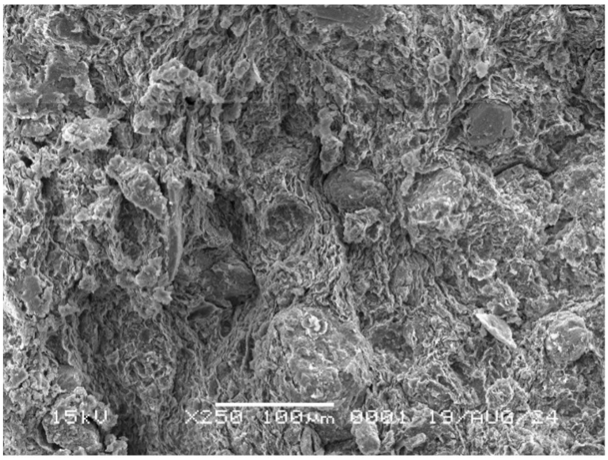
A total of four (4) claystone samples—GNK 4, GNK 7, GNK 9, and KND 1—from the Damar Formation in the southern coastal areas of Semarang and Kendal, Central Java, were carefully examined using SEM device. These claystone samples were retrieved from the cores of drilling wells. Sample GNK 4 was taken from the shallowest depth, followed sequentially by GNK 7, GNK 9, and KND 1. Microphotographs showing key constituents or features of the rock samples are presented in Figures 3–6.

Types and Physical Characteristics of Clay Minerals

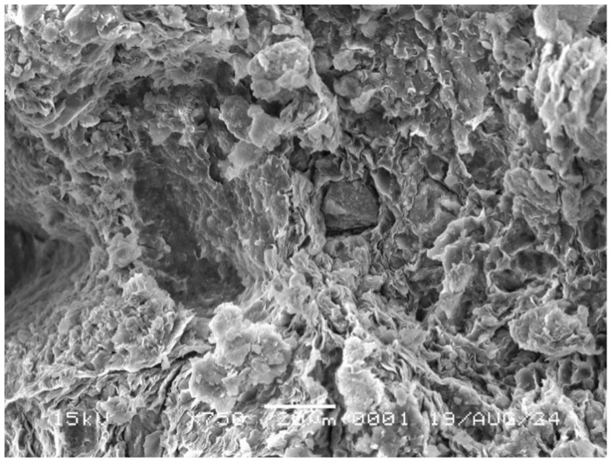
SEM analysis confirms that the studied samples are generally composed of clay minerals, including illite (K1-1.5Al4(Si7-6.5Al1-1.5O20)(OH)^4, smectite (1/2Ca)0.7(Al,Mg,Fe)4 (Si,Al)8O20).nH2O and kaolinite (Al4(Si4O10)(OH)^8, and a mixture of illite-smectite. Organic matter content ranges from less than 1% of the total sample volume. Clay materials typically consist of one or more clay minerals such as illite, smectite, and kaolinite, often accompanied by fine-grained quartz, feldspar, and other detrital minerals, depending on the depositional environment (Baldermann *et al.*, 2020; Ibrahim *et al.*, 2020). Vertical distribution of clay minerals in the samples reveals a distinct pattern: smectite is absent in the lower sections of the study site, while the proportion of illite–smectite mixed layers increases toward the top (Peltz *et al.*, 2024). The abundance of illite–smectite in the upper samples is interpreted as a product of volcanic activity in the surrounding area.

Samples from the Genuk region appear compact and dense.The claystone is characterized by the presence of crenulated textures and flaking surfaces derived from illite clay minerals, sheet-like structures of kaolinite, and signs of feldspar mineral dissolution (Ren *et al.*, 2020; Zhong *et al.*, 2024). Mudstone is distinguished by the occurrence of illite with crenulated textures, evidence of feldspar dissolution, and quartz overgrowth features.

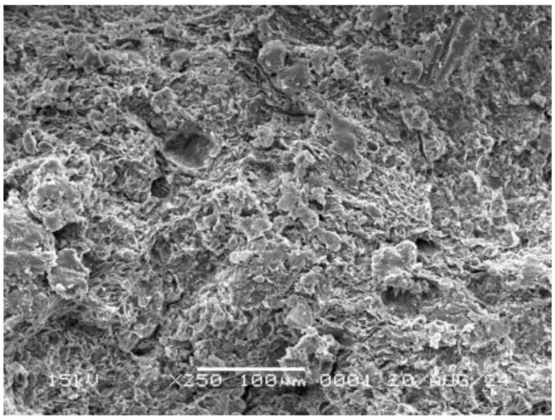
(3A)



(3B)



(3C)



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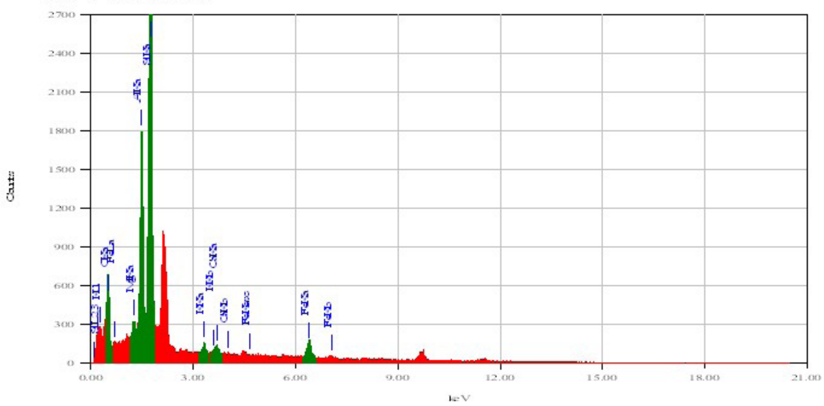
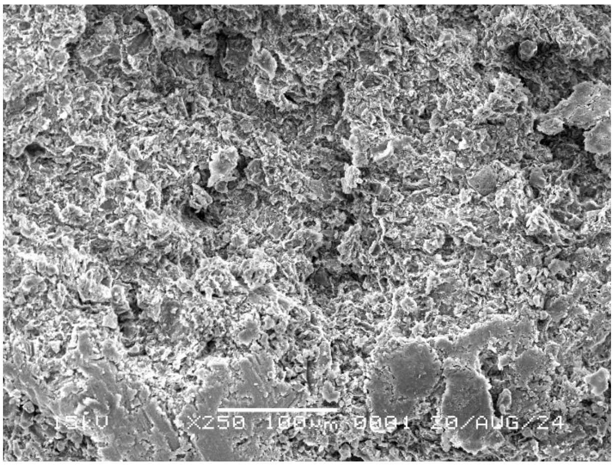
GNK 4 SEM 250x a

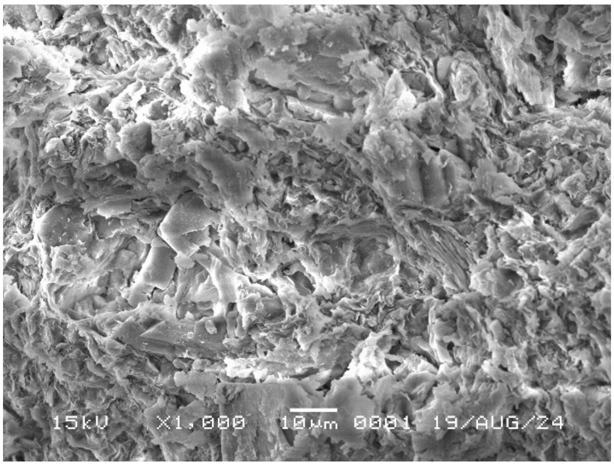


Element	(keV)	mass%	Error%	At%	Compound	mass%	Cation	K
O		47.12						
Mg K	1.253	0.85	0.23	2.35	MgO	1.41	0.29	1.3452
Al K	1.486	11.49	0.27	14.31	Al2O3	21.71	3.47	20.6856
Si K	1.739	28.95	0.35	69.26	SiO2	61.94	8.40	53.9613
K K	3.312	1.12	0.33	0.96	K2O	1.35	0.23	2.5020
Ca K	3.690	1.10	0.46	1.85	CaO	1.55	0.22	2.6210
Fe K	6.398	9.36	1.21	11.26	FeO	12.04	1.37	18.8849
Total		100.00		100.00		100.00	13.98	

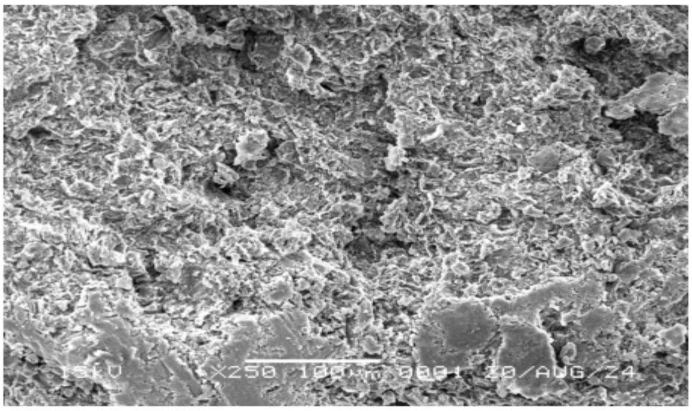
Figure 3. SEM microphotograph of sample GNK-4, collected from the Genuk region, showing clay minerals predominantly composed of mixed-layer illite–smectite and kaolinite (3A and 3B), 3C is EDX analysis microphotograph

(4A) (4B)





(4C)



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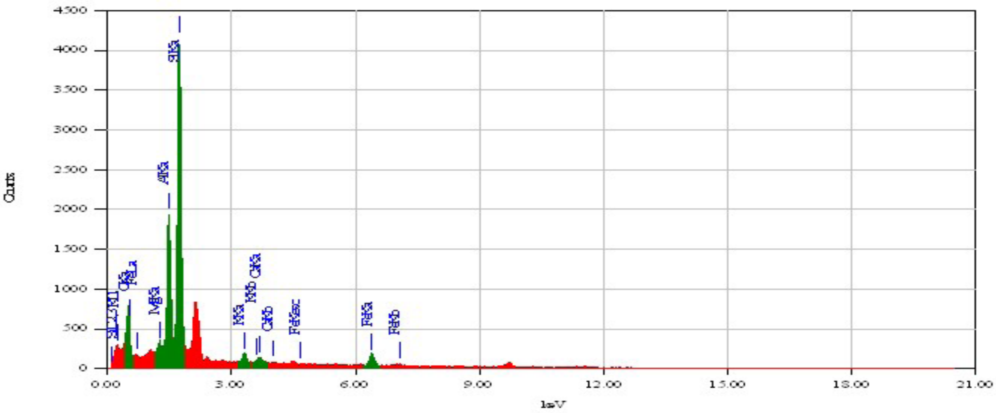
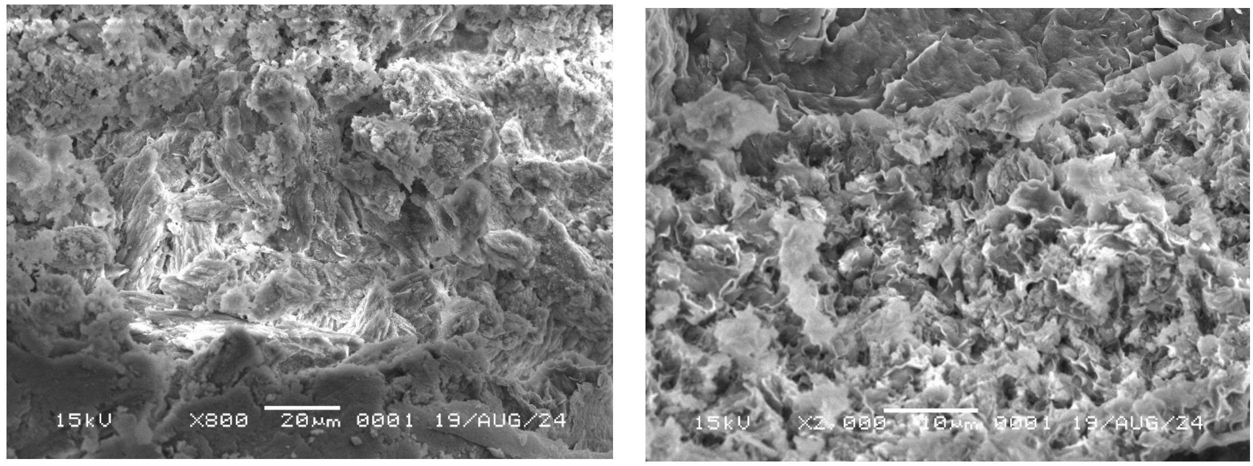
GNK 7 SEM 250x a



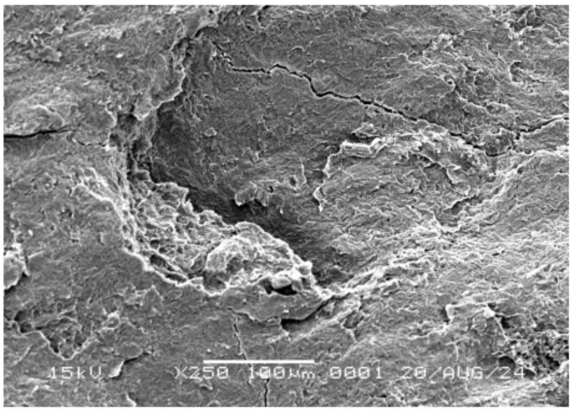
Element	(keV)	mass%	Error%	At%	Compound	mass%	Cation	K
O		46.78						
Mg K	1.253	0.79	0.20	2.18	MgO	1.30	0.27	1.2273
Al K	1.486	11.42	0.23	14.27	Al2O3	21.59	3.48	20.3511
Si K	1.739	28.56	0.30	68.55	SiO2	61.10	8.35	52.7451
K K	3.312	1.71	0.28	1.48	K2O	2.06	0.36	3.7964
Ca K	3.690	1.17	0.39	1.97	CaO	1.64	0.24	2.7502
Fe K	6.398	9.57	1.01	11.55	FeO	12.31	1.41	19.1300
Total		100.00		100.00		100.00	14.09	

Figure 4. SEM microphotograph of sample GNK-7, collected from the Genuk region, showing clay minerals predominantly composed of mixed illite–smectite and kaolinite (4A and 4B), 4C is EDX analysis

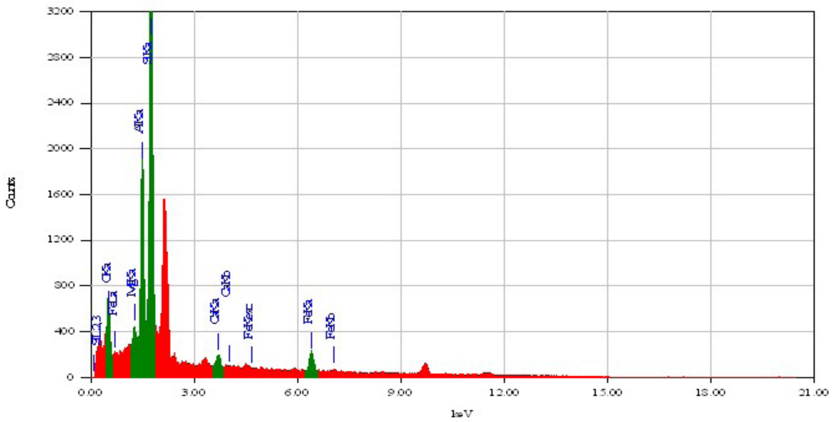
(5A) (5B)



(5C)



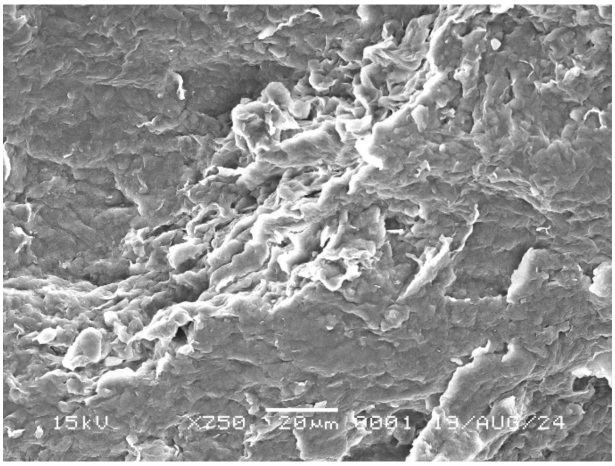
GNK 9 SEM 250x

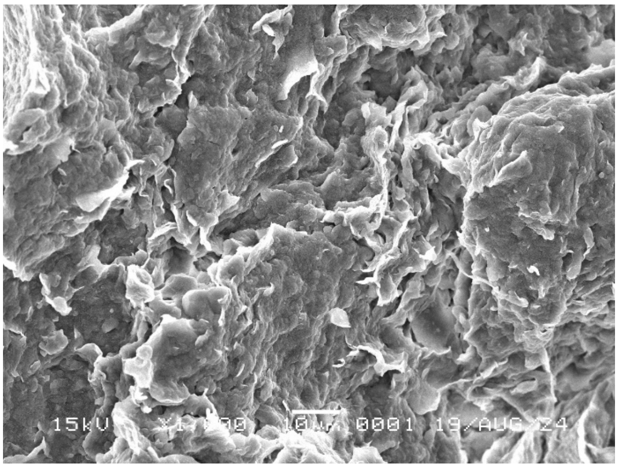


Element	(keV)	mass%	Error%	At%	Compound		mass%	Cation	K
O		46.84							
Mg K	1.253	1.00	0.31	2.74	MgO	1.66	0.34	1.5563	
Al K	1.486	10.81	0.35	13.33	Al2O3	20.43	3.28	19.1665	
Si K	1.739	28.77	0.46	68.17	SiO2	61.54	8.40	53.3451	
Ca K	3.690	1.62	0.59	2.68	CaO	2.26	0.33	3.8450	
Fe K	6.398	10.96	1.55	13.06	FeO	14.10	1.61	22.0870	
Total		100.00		100.00		100.00	13.96		

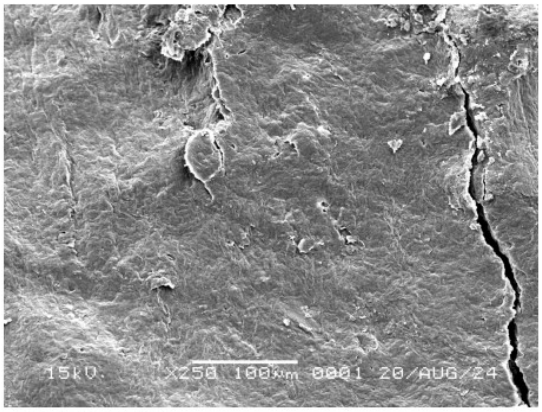
Figure 5. SEM microphotograph of sample GNK-9, collected from the Genuk region, showing clay minerals predominantly composed of mixed-layer illite–smectite and kaolinite (5A and 5B), 5C is EDX analysis

(6A) (6B)





(6C)



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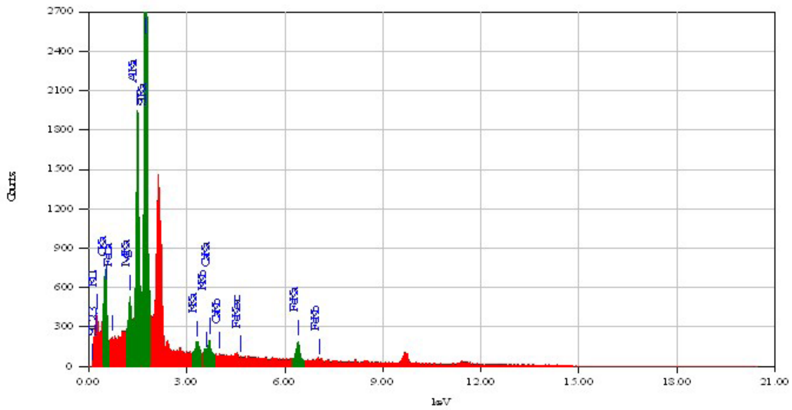
KND 1 SEM 250x



Element	(keV)	mass%	Error%	At%	Compound	mass%	Cation	K
O		47.37						
Mg K	1.253	1.35	0.26	3.69	MgO	2.25	0.45	2.1598
Al K	1.486	10.56	0.30	12.96	Al2O3	19.95	3.17	19.0330
Si K	1.739	29.76	0.40	70.17	SiO2	63.67	8.59	55.9614
K K	3.312	1.29	0.38	1.09	K2O	1.55	0.27	2.8799
Ca K	3.690	1.37	0.52	2.26	CaO	1.91	0.28	3.2431
Fe K	6.398	8.30	1.37	9.84	FeO	10.67	1.20	16.7230
Total		100.00		100.00		100.00	13.96	

Figure 6. SEM microphotograph of sample KND-1, collected from Kendal, showing clay minerals predominantly composed of kaolinite (6A and 6B), 6C is EDX analysis

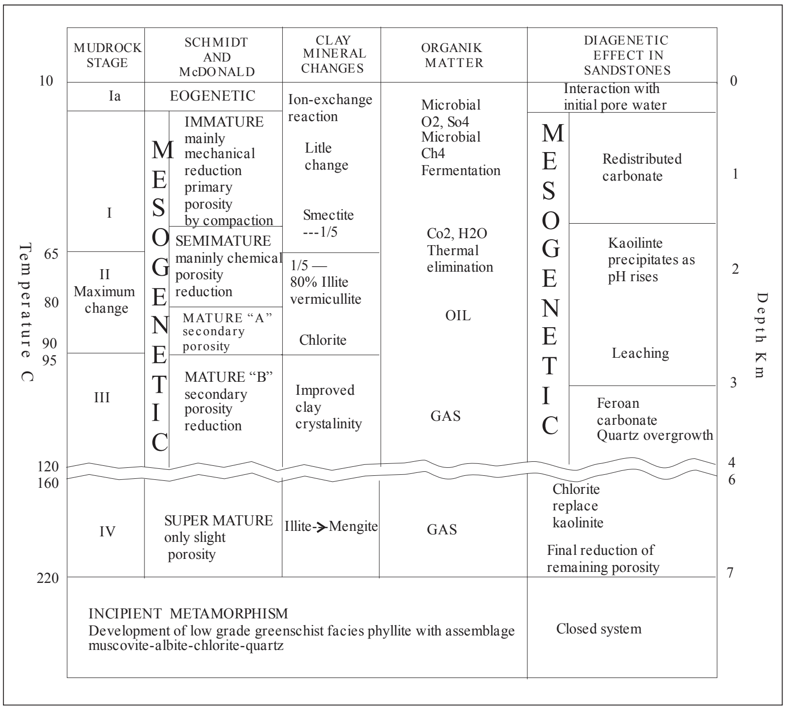


Figure 7. The relationship between the level of diagenesis and the depth of the embankment, adapted from Burley *et al.* (1987)

Diagenesis

SEM analysis reveals the presence of clay minerals such as smectite, kaolinite, illite and features like quartz overgrowth. Based on these characteristics, it is interpreted that the analysed rock samples are at the middle mesodiagenetic stage, marked by the presence of dissolution features. One sample, however, shows evidence of quartz overgrowths, suggesting it has reached the late mesodiagenetic stage. These interpretations align with the diagenetic classification of sedimentary rocks from the Damar Formation as proposed by Burley (1987), who categorized such features within late diagenesis groups II and III. This classification corresponds to the mature mesogenetic stages A and B, as defined by Schmidt and McDonald (1979). Group II diagenesis is associated with burial depths of 2500–2750 m and temperatures ranging from 80°C to 92°C, whereas Group III occurs at depths of 3000–4000 m with temperatures between 95°C and 120°C (Figure 7).

DISCUSSION

The presence of illite-smectite in the upper part of the Damar Formation indicates differing depositional environments for the lower and upper mudstones. However, the similarity in clay mineral composition suggests that the claystone has undergone a comparable diagenetic history. Illite is a 2:1 potassium-rich dioctahedral mica silicate clay mineral characterized by missing interlayers, elevated potassium and aluminium contents, low iron concentration, fine grain size, and notable resistance to corrosion and mechanical toughness. As a non-expanding phyllosilicate belonging to the mica group, illite exhibits excellent physical and chemical properties such as abrasion resistance, fluidity, absorption, and heat resistance. Its crystal structure and composition closely resemble montmorillonite, with key differences including: (a) potassium ions acting as charge balancers and binders between crystal layers, and (b) approximately 20% of silicon atoms on tetrahedral sheets replaced by aluminium (Wang *et al.*, 2021; Zhao *et al.*, 2023).

The presence of kaolinite in the mudstone indicates formation under aerobic conditions. Its crystal morphology suggests that kaolinite is either a secondary or early diagenetic mineral, likely derived from feldspar weathering. Kaolinite frequently occurs within the smectite-rich groundmass, suggesting it precipitated after the smectite matrix formed (Li *et al.*, 2020; Singh *et al.*, 2022).

Generally, smectite minerals display irregular (disoriented) structures, although some may show preferred orientation. The density of smectite varies from low to moderate, indicating minimal burial loading. Smectite is considered a primary depositional component, likely sourced from volcanic material deposited in a marine environment. The presence of smectite in the upper Damar Formation implies a risk of swelling, due to smectite's well-known property of significant expansion upon water exposure. This swelling poses hazards to soil bearing capacity and foundation stability, as expansion-induced instability can compromise overlying structures. Clay mineral analysis in the study area confirms that smectite readily expands with increasing water content, generating expansion pressures capable of damaging lightweight constructions (Kim *et al.*, 2022; Patel *et al.*, 2023).

Volcanic deposits such as tuffaceous sandstone, conglomerate, medium to fine sandstone, and polymictic breccia in the middle and lower parts of the Damar Formation likely result from epiclastic reworking of Miocene volcanic arcs active in southern Kendal and Semarang areas. These deposits correlate with the Old Andesitic Formation (OAF) (Ramli *et al.*, 2021).

SEM analysis indicates that the mudstone has undergone mesodiagenesis, suggesting burial at depths of approximately 2500 to 4000 m and temperatures ranging from 80 to 120°C (Burley *et al.*, 1987; Chen *et al.*, 2020). The burial history is supported by illite-smectite minerals typically formed under elevated pressure and temperature. The flaky texture of illite further confirms significant burial, while quartz overgrowths are characteristic of rocks that have undergone late mesodiagenesis (Burley *et al.*, 1987; Gupta *et al.*, 2022).

Sample KND-1 from the upper Damar Formation is dominated by authigenic kaolinite, likely formed under wetter climatic conditions and linked to increased groundwater flow or extensive meteoric water flushing through fluvial sandstone. This kaolinite precipitated at shallower depths, indicating lower formation temperatures of approximately 25 to 80°C and representing a more proximal depositional environment compared to Genuk samples. Conversely, upper Damar Formation samples GNK-4, GNK-7, and GNK-9 are dominated by illite-smectite with rare authigenic kaolinite and are rich in FeK and FeO. These likely formed in tidal or estuarine environments. The Genuk area illustrates that with increasing burial depth, compaction becomes more chemically driven and increasingly influenced by temperature rather than effective stress (Yuan *et al.*, 2021; Oliveira *et al.*, 2023).

CONCLUSION

SEM and clay mineral analysis indicate that the fine-grained sedimentary rocks of the Damar Formation have undergone diagenesis from middle to late mesodiagenesis stages. This is indicated by the presence of illite-smectite, flaky-textured illite, feldspar dissolution, and quartz overgrowth features that suggest burial at depths of 2500–4000 m and temperatures of around 80–120°C. Despite differences in depositional environment, the consistent clay mineral composition across the formation suggests a similar diagenetic trajectory. Kaolinite in some samples point to shallower meteoric conditions, while illite-smectite in others reflects deeper, possibly estuarine settings. The presence of swelling-prone smectite in the upper part of the formation poses potential geotechnical risks for construction, underscoring the need for careful land-use planning. Overall, the Damar Formation records a coherent burial and thermal history with localized variations in fluid influence and depositional setting.

ACKNOWLEDGEMENTS

The authors thank Head of the Center for Geological Survey for supporting to publish this paper. The authors are greatly indebted to colleagues who gave valuable discussions during fieldwork and laboratory activities.

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