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The Physical Appearance and Depositional Environment of The Upper Damar Formation: Alertness from The Deep Pile Benchmark, Field Test, and Laboratory Data in Elucidating Land Subsidence Potential in Kendal-Semarang, Northern Coast of Central Java

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Abstract - This paper examines the phenomenon land subsidence occurring in Kendal-Semarang, on the northern coast of Central Java Province (Java Island, Indonesia). Previous studies suggested that anthropogenic processes, particularly the over-exploration of groundwater, caused land subsidence in Kendal City and northern Semarang City. However, the geological factors such as sedimentology and stratigraphy below the Holocene deposit are possibly contributing to land subsidence in the Kendal-Semarang area remain unclear. This paper aims to analyze the stratigraphy, sedimentology, and insight into compaction and land subsidence potential of the basement Kendal-Semarang region within the Pliocene-Pleistocene Upper Damar Formation, based on measured sections in selected areas, analysis of deep pile benchmarks, and geotechnical aspects by using Standard Penetration Test (SPT) analysis. Specifically, it investigates the relationship between sediment loading and recent geological changes, related natural phenomena, erosion, and sedimentation, that may influence land stability. Detailed stratigraphic analyses were conducted in six selected locations through field measurements and borehole data to achieve this. These data were complemented by foraminifera and pollen analyses used to date the formation accurately. The stratigraphic interpretation suggests that during the Middle to Late Pliocene, the deposition environment of the Damar Formation transitioned from an upper delta plain to a tidal-influenced pro-delta environment. Two deep-pile benchmarks were also installed to monitor land movement, which revealed significant subsidence over one month, with rates of approximately 2.4 to 2.9 millim per month. These findings are supported by Standard Penetration Test (SPT) results, indicating that the underlying black and grey clay of the Upper Damar Formation-serving as the basement rock-exhibits N-SPT values between 5 and 27, ranging from firm to very stiff. Additionally, SEM analysis showed the prevalence of illite-smectite clay minerals, suggesting a moderate to high potential for compression and settlement under wet conditions. Understanding the compaction behaviour of these sediments helps explain ongoing land subsidence issues in the region, which is crucial for land use planning, infrastructure development, and hazard mitigation.

Keywords: Land subsidence, deep pile benchmark, Damar Formation, SEM, SPT analysis, Kendal-Semarang

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Introduction

The northern part of Central Java accommodates approximately 60 % of the province population. This region is particularly vulnerable to land subsidence (Abidin *et al*., 2013), especially in flat, low-lying areas where sediment accumulates in alluvial or delta environments (Figure 1). Land subsidence has significant implications for urban development, infrastructure stability, agriculture, and coastal groundwater management. In low-lying coastal areas, substantial subsidence may also enhance the risk of seawater intrusion.

Central Java features a notable re-entrant, or indentation, along its coastline compared to western and eastern Java. The Eurasian and Indian Oceanic Plates, which have been converging since the Jurassic-Cretaceous period, actively interact at the edge of Java Island. The basement of Java consists of Eurasian continental crust in northern West Java and Central Java, as well as accreted terranes in southern West Java, southern Central Java, and nearly all of East Java Java (Metcalfe, 2011). These tectonic features - resulting from convergence - have given rise to subduction trenches, magmatic-volcanic arcs, accretionary prisms, and back-arc and fore-arc basins. Sedimentary and volcaniclastic rocks, intruded by various magmatic formations, overlay the basement rocks. Central Java serves as a transitional zone between the predominantly continental basement of West Java and the intermediate basement of East Java.

The geological conditions in Central Java, particularly along its northern coastline, are influenced by complex tectonic dynamics occurring in the vicinity of the Eurasian and Indo-Australian plates. This region experiences active tectonic processes that have resulted in the formation of various geological features such as faults, folds, and areas of accelerated surface processes. In the northern coastal areas of Central Java, including Kendal and Semarang, the Quaternary sediments and deltaic depositional environments are significantly affected by these tectonic activities. Additionally, subduction zones and volcanic activities in the region further influence the lithology and sedimentation patterns, contributing to a highly dynamic depositional environment. These tectonic interactions also play a crucial role in determining the distribution of geological layers, the emergence of specific lithologies, and the stability of the terrain, ultimately impacting the risk potential of natural disasters in the coastal areas such as Kendal and Semarang.

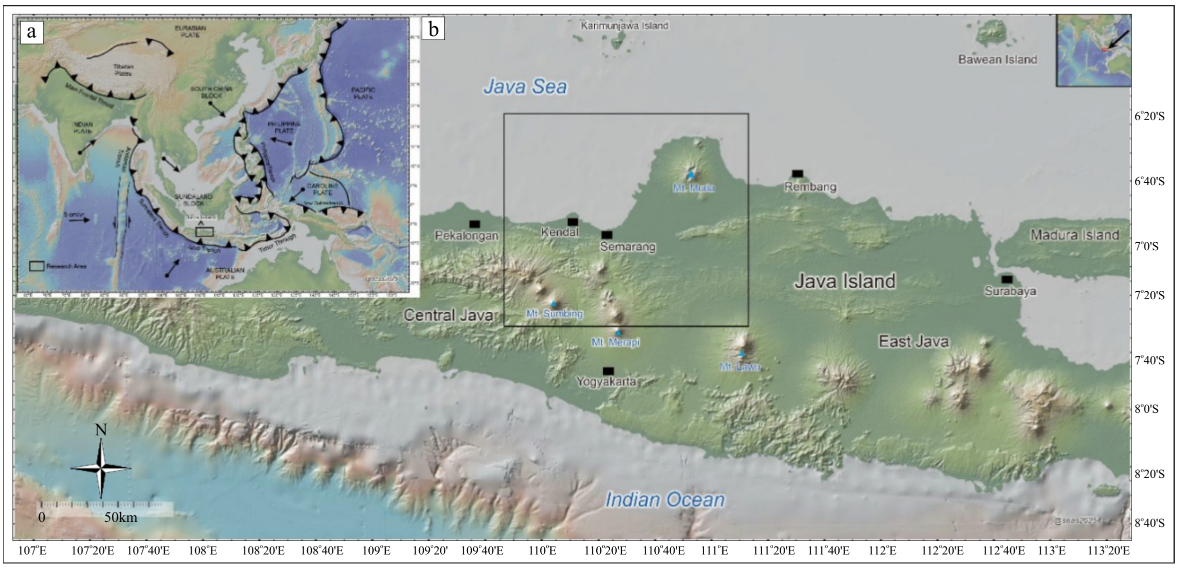


Figure 1. Location of the researched area. (a) The plate tectonic setting of Southeast Asia, which includes plate boundaries, major structures, and plate motion direction, follows Metcalfe (2011). (b) Location of Kendal -Semarang in the northern coastal area of Java Island, whereas the southeast margin of the Sundaland Block is shown as a black rectangle in (a). The figure base was made with GeoMapApp (www.geomapapp.org). (The image is CC by Ryan *et al.,* 2009).

The northern part of Central Java accommodates approximately 60% of the province's population. This region is particularly susceptible to land subsidence, especially in flat, low-lying areas where sedimentation occurs within alluvial or deltaic environments (see Figure 1). Land subsidence carries significant implications for urban development, infrastructure stability, agriculture, and coastal groundwater management. In coastal low-lying zones, pronounced subsidence may also exacerbate the risk of seawater intrusion.

This study seeks to clarify the phenomenon of land subsidence in the northern coastal regions of Central Java, specifically in Kendal and Semarang, from a geological standpoint. A novel finding of this research is the identification of clay minerals, specifically illite and smectite, which are significant factors contributing to land subsidence in Semarang-Kendal and throughout the entire Northern Coastal Central Java region. Furthermore, data from deep pile benchmarks in the Kendal-Semarang area support the study, revealing substantial rates of land subsidence. An additional innovative aspect of this paper is the presentation of the compression index values for the basement rocks of the Kendal-Semarang region, namely the lower part of the Upper Damar Formation, which indicates a medium to high potential for land subsidence. Stratigraphic and geological structural data from the selected sites further corroborate the subsidence model, suggesting that the northern coastal area of Central Java is part of a subsiding block situated along the boundary between Neogene to Pliocene rocks and the youngest sediments of Holocene alluvium.

Materials and Methods

This study involves area (Figure 2) and the measurement of stratigraphic sections in Damar River, the Weleri Subdistrict (Figure 3).

According to Thanden *et al.* (1996), the geological history of the Magelang and Semarang Quadrangles began in the Early Cenozoic, evidenced by basaltic and andesitic intrusions followed by uplift and erosion. This erosion resulted in the formation of turbidites of the Kerek

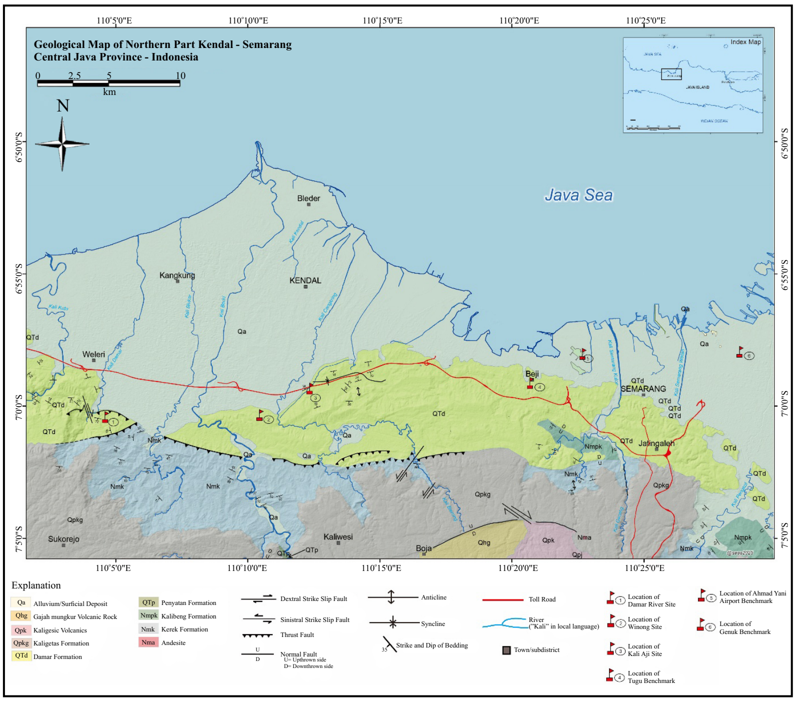


Figure 2. Geological map of Kendal-Semarang, the northern coastal area of Central Java Province. Reinterpreted and updated from the 1:100,000 scale geological maps of Thanden *et al.*, 1996, and fieldwork during December 2024 . The map attached shows the location of the benchmark discussed in this paper.

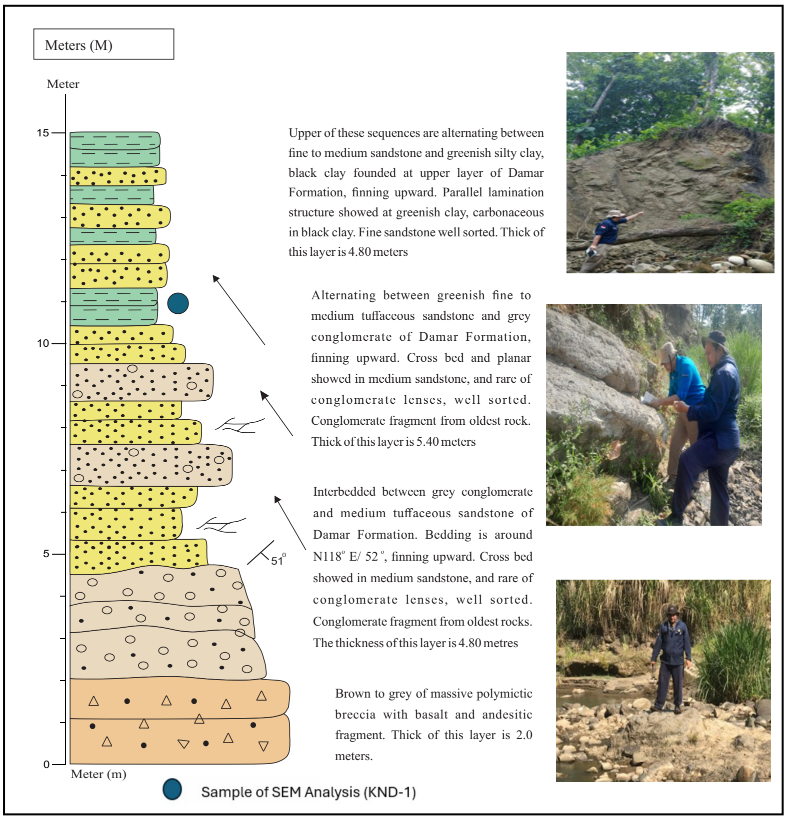
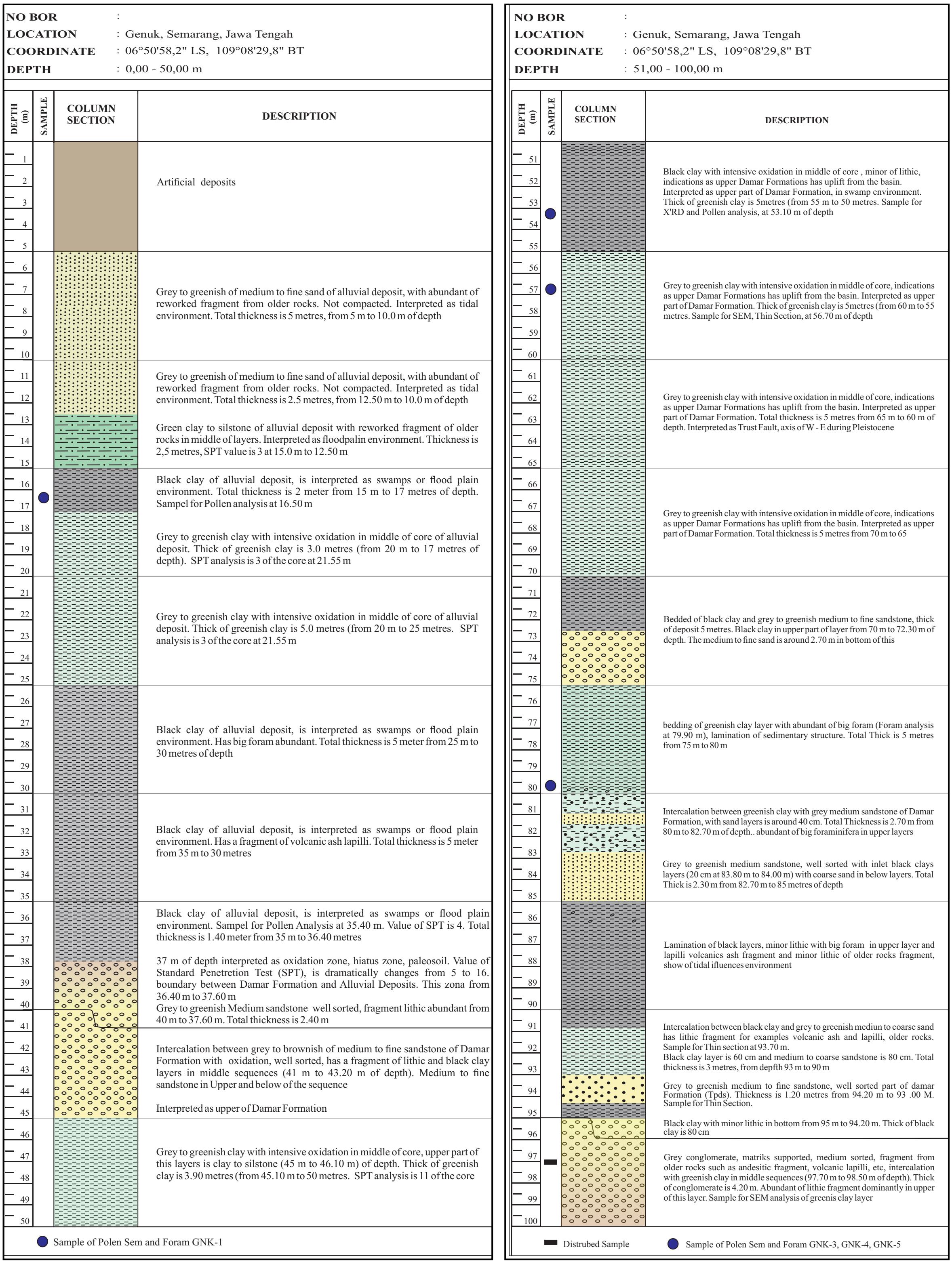


Figure 3. A measured section of stratigraphic sequence was taken on the 4th of December 2024 in the type locality of the Damar Formation at the Damar River, the Weleri Subdistrict, showing fining upwards from the lower to the middle of its formation. The thickness of this sequence is around 15 m.

Formation in neritic environments, succeeded by the Kalibeng Formation in bathyal environments, and ultimately the basin fill of the Damar Formation, which transitioned from transitional to terrestrial environments. Tectonic activity during the Plio-Pleistocene reactivated deformation from the Early Cenozoic, producing predominantly east-west (E-W) asymmetrical folds, along with E-W thrust faults, NE-SW, and NW-SE strike-slip faults, as well as normal faults. The fractures created a weak zone that facilitated the ascent of young Quaternary volcanic rocks.

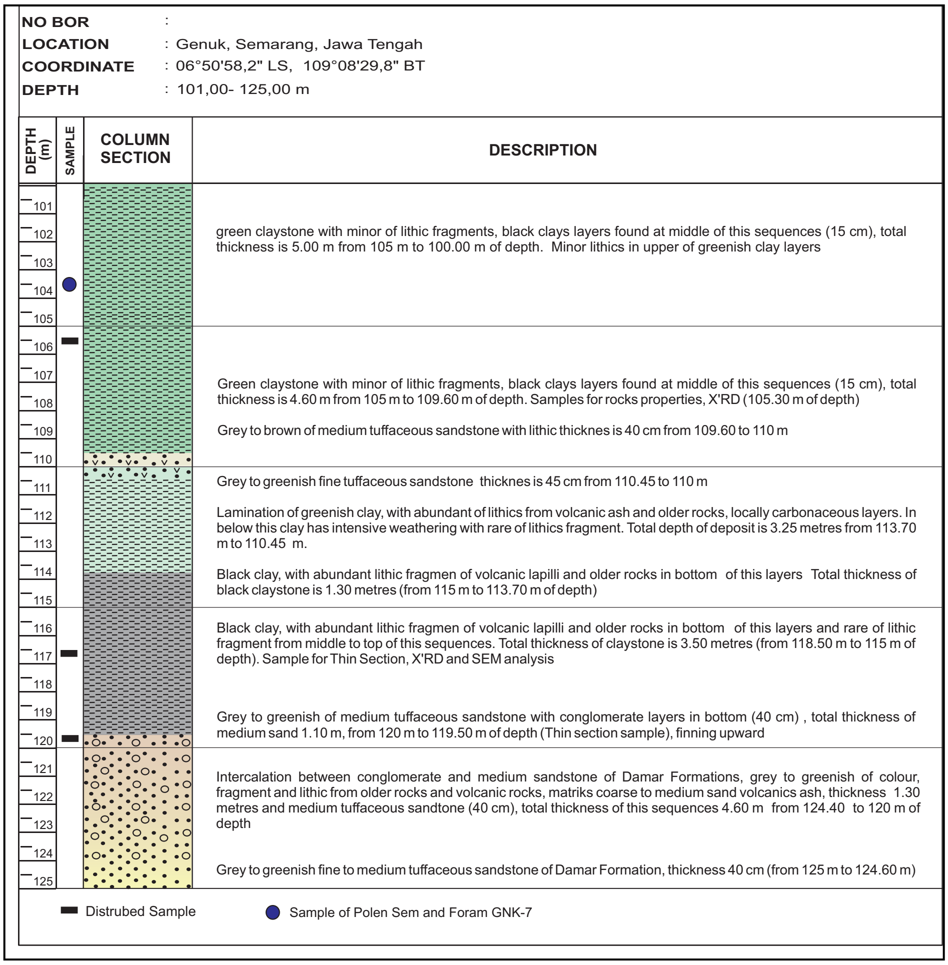
This study utilized well-log data obtained from boreholes in The Genuk District (Figure 4). Laboratory analyses focused on biostratigraphy of the Pliocene-Pleistocene Upper Damar Formation. Representative core samples were collected from Genuk for laboratory testing, including assessments of rock properties, foraminifera, and pollen analysis to reconstruct paleoenvironment, depositional processes, and the potential for land subsidence, particularly within the upper greenish and black clay layers of the Damar Formation. Pollen and foraminifera analyses were performed on four samples at the Centre for Geological Surveys, Geological Agency.

Four sedimentary rock samples from the Upper Damar Formation, collected from Genuk borehole in the southern coastal zones of Semarang and Kendal, were analyzed using Scanning Electron Microscopy (SEM). The microphotographs obtained highlight key mineral constituents and textures. This article presents a summary of SEM results regarding clay mineral characteristics and mineral compositions of each sample. The samples, labeled GNK-4 (Figure 5), GNK-7 (Figure 6), GNK-9 (Figure 7), and KND-1 (Figure 8) were prepared by cutting into small blocks of approximately 20 mm³, cleaned with compressed air, attached to a stub with conductive glue containing metal powder, and coated with a thin layer of gold in a vacuum evapora-



Figures 4. (a), (b), and (c) show the borehole stratigraphic section from the Genuk Deep Pile Benchmark. The depth of the Genuk borehole is approximately 125 m. The log bore has six samples for foraminifera and pollen analyses at different depths. The Genuk area is interpreted as a distal facies in the foreland basin setting compared with the Damar River or Winong Quarry.

tive coater. SEM analysis aimed to elucidate the physical characteristics, diagenetic processes, and implications for rock history, including grain relationships, clay matrices, cementation, textures,



Figures 4. Continued...

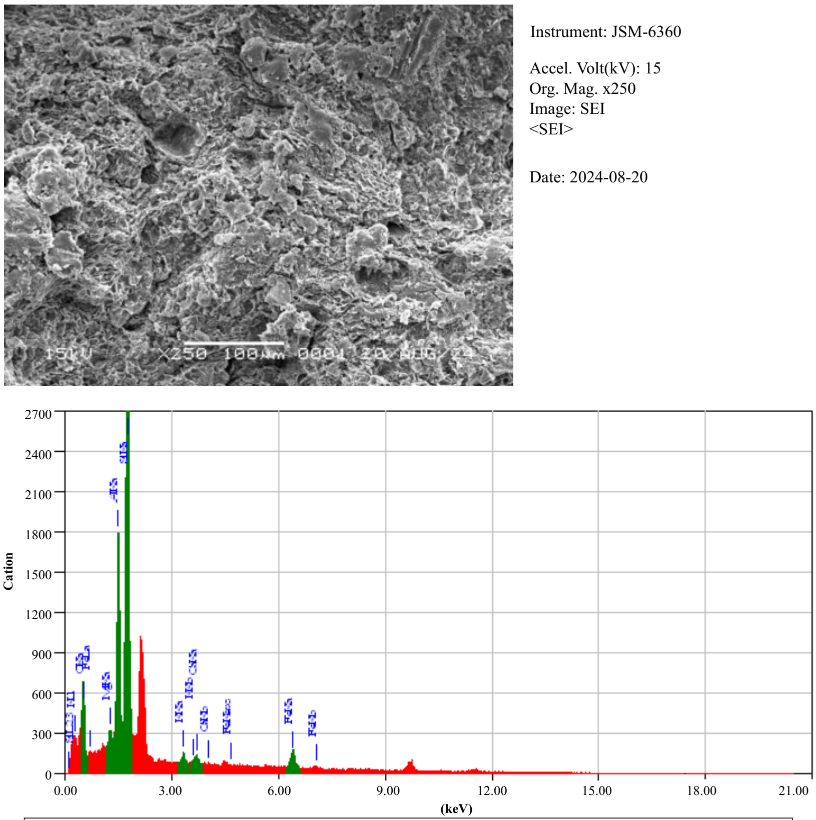
mineral types, cavity structures, and orientations at the micron scale (Pittman, 1979).

Additionally, geotechnical analyses, including the Standard Penetration Test (SPT) and deep pile benchmarks, were conducted at various locations in Kendal and Semarang (Figure 2). The SPT involves driving a split-spoon sampler into the ground using a 63.5 kg hammer dropped from a height of 0.76 m and recording the number of blows required to penetrate 300 mm. The test was performed in three stages, each 150 mm thick; the number of blows for each stage was summed to determine the N-value (blows per 0.3 m). The first stage is recorded as a seat, while the number of strokes to enter the second and the third stages is added up to obtain the N-stroke value or SPT resistance (expressed in strokes/0.3 m) (Badan Standardisasi Nasional, 2008). The results were interpreted according to Wajoh and Mallo (2014).

For the deep pile analysis, a pile was constructed at Genuk and Tugu in Semarang to assess soft soil thickness and subsurface compaction potential related to land subsidence (Figures 9 and 10). The data from borehole logs and geotechnical testing provided detailed insights into the stratigraphy, soil strength, and consolidation behaviour of the sediments.

Index Compressibility Analysis

Terzaghi one-dimensional consolidation theory posits that their compressibility properties predominantly determine the extent of primary settlement in saturated soils. The primary parameter used to quantify this behaviour is the Compression Index (Cc), defined as the slope of the void ratio versus the logarithm of the effective stress curve within the virgin compression range (Terzaghi and Peck, 1967; Bell, 2007). This



Element	(keV)	masss%	Eror%	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	Al_2O_3	21.71	3.47	20.6856	
Si K	1.739	28.95	0.35	69.26	SiO_2	61.94	8.40	53.9613	
K K	3.312	1.12	0.33	0.96	K_2O	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 5. Microphotograph SEM showing clay mineral dominantly of mixed-layer clay (illite-smectite) and kaolinite from the Genuk areas (GNK-4).

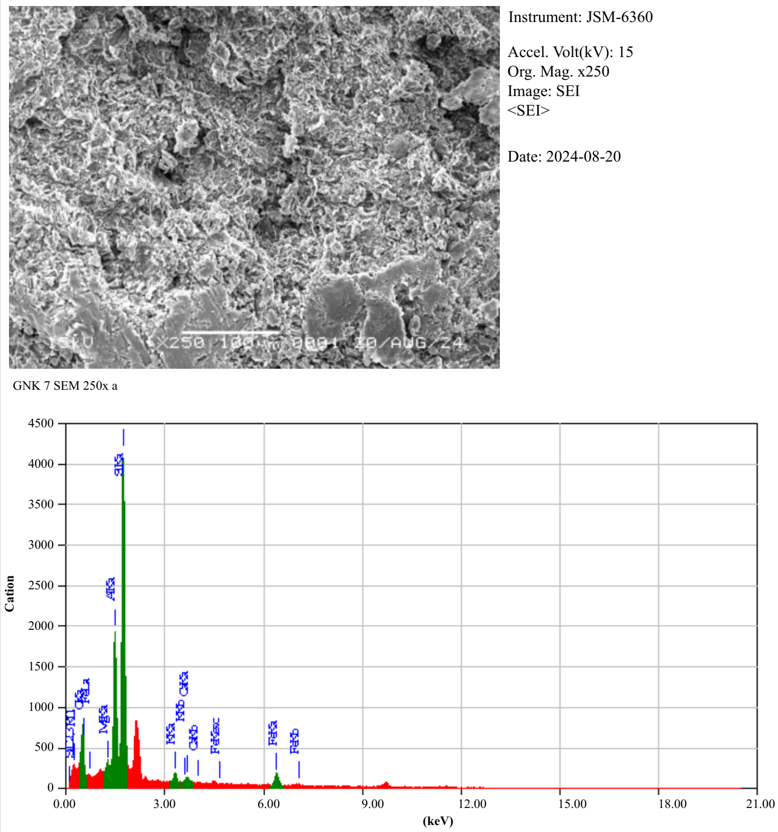
parameter is extensively utilized for normally consolidated clays, offering a practical approach to estimate compressibility and subsequent settlement of soft cohesive deposits. Table 1 presents an approximation of soil compressibility based on Cc values (Bell, 2007).

Result and Analysis

The Damar Formation is well exposed at the Winong Quarry (Figure 11) and Kali Aji, (Figure 12) in Kendal District. The lower part of this formation consists of dark grey, polymictic breccia, with a matrix of medium- to coarse-grained sand. The deposits contain fragments of andesite, basalt, and older rocks. These sediments likely accumulated in a foreland basin during the Late Pliocene. The breccia, which is approximately 4.4 m thick, is intercalated with or overlies fluviatile conglomerate and medium- to fine-grained sandstone sequences. These volcanic and sedimentary units represent the basal part of the Damar Formation.

Foraminifera And Pollen

Well-log data analyses from the Genuk boreholes provide detailed age constraints for the Upper Damar Formation based on foraminiferal and palynomorph assemblages. Foraminifera were identified following Blow (1969), Barker (1960), and Bolli (1985), while palynomorph identification was based on Morley (1991).



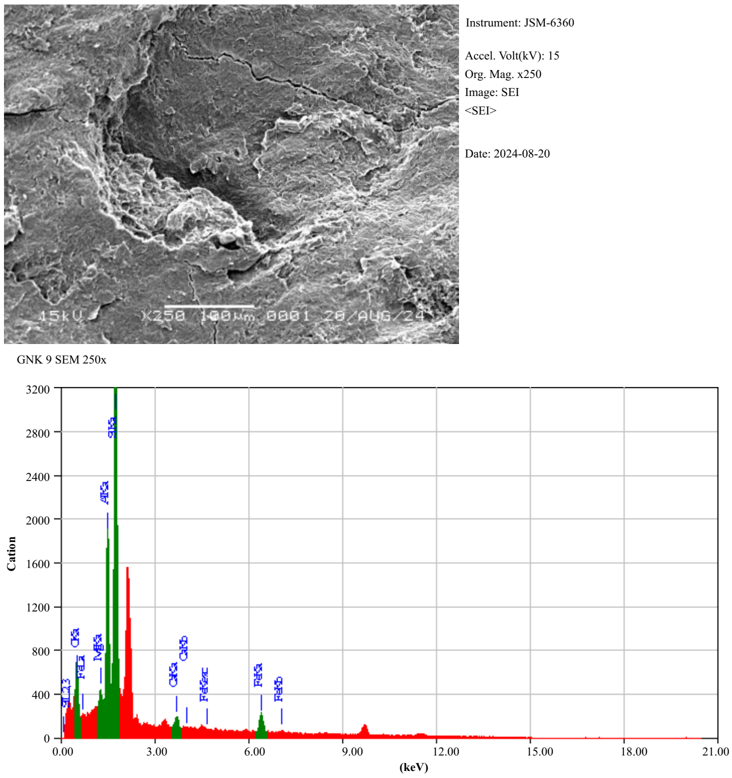
Element	(keV)	masss%	Eror%	At%	Compound		mass%	Cation	K
O		46.78							
Mg K	1.253	0.79	0.20	2.18	MgO	1.30	0.27	1.2273	
Al K	1.486	11.42	0.23	14.27	Al_2O_3	21.59	3.48	20.3511	
Si K	1.739	28.56	0.30	68.55	SiO_2	61.10	8.35	52.7451	
K K	3.312	1.71	0.28	1.48	K_2O	2.06	0.36	3.7964	
Ca K	3.690	1.17	0.39	1.97	CaO	1.64	0.24	2.7502	
Fe K	6.398	9.57	1.01	11.55	FeO	12.64	1.41	19.1300	
Total		100.00		100.00		100.00	14.09		

Figure 6. Scanning electron micrograph illustrating the predominance of mixed-layer clay minerals (illite-smectite) and kaolinite in samples obtained from the Genuk area (GNK-7).

In borehole GNK 1, 16.50 m depth (Table 1, Figures 13 and 14), planktonic foraminifera species such as *Globigerinoides trilobites immaturus LeRoy* - *Orbulina universa d'Orbigny, Globorotalia acostaensis acostaensis Blow, Globorotalia sp., Globigerinoides bulloideus Crescenti, Globigerinoides sp., Globigerinoides ruber d'Orbig* were identified. The presence of *Globigerinoides ruber* corresponds to Pliocene to Pleistocene age, specifically within zone N18-N23 (Blow, 1969).

Fourteen Benthic foraminifera identified in this interval include *Asterotalia subtrispinosa, Asterorotalia trispinosa (Thalmann), Lagena sp, Rotalia beccarii Linné, Elphidium discoidale (d'Orbigny), Nonion sp. Elphidium advenum Cushman, Bolivina spp. Spiroloculina communis Cushman and Todd, Quenqueloculina compta Cushman* - *Tubinella sp*. The abundance of *Tubinella sp.* typically found in inner neritic depositional environments (0 - 30 m depth), suggests deposition occurred near the shoreline. The Palynological analysis revealed 223 pollen and spore specimens in GNK-1, with spores more abundant than pollen (Table 2). The presence of mangrove pollen, such as *Florschuetzia levipoli* (Lythraceae), *Rhizophora sp*. (*Rhizophoraceae*), and *Dinoflagellata,* but also Foraminifera Lining Test (FLT), confirms deposition in a shallow marine to mangrove transitional environment.

In GNK-5 samples, (depth 79,70 m), the foraminifera planktonic assemblages include *Globorotalia spp. Globigerinoides bulloideus*



Element	(keV)	masss%	Eror%	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	Al_2O_3	20.43	3.28	19.1665	
Si K	1.739	28.77	0.46	68.17	SiO_2	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 7. SEM micrograph depicting the predominance of mixed-layer clay minerals (illite-smectite) and kaolinite in samples from the Genuk Area (GNK-9).

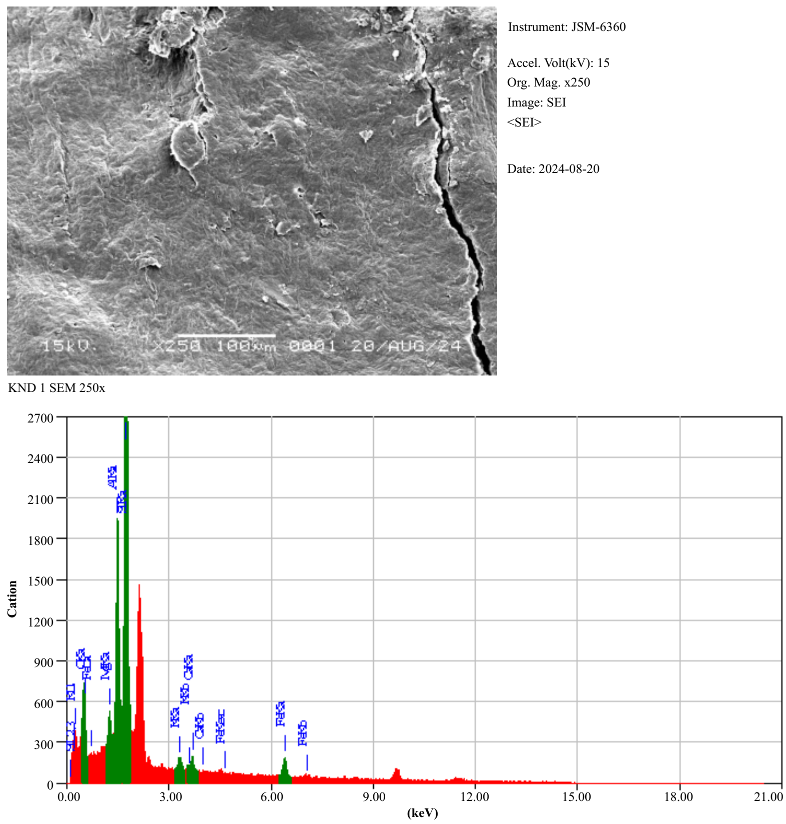
Crescenti, Globorotalia acostaensis acostaensis Blow, *Globigerinoides spp. Indeterminate fossil*. The presence of index fossils such as *Globorotalia acostaensis acostaensis and Pseudorotalia indopacifica* (Thalmann) confirms a Late Pliocene age (zone N21) and indicates a depositional setting ranging from an inner to middle neritic (0-100 m).

Palynological samples from GNK-2, GNK-3, and GNK-4 also revealed lowland terrestrial pollen (*Polvadovellenites vancompei, Moraceae*) and mangrove elements (*Florschuetzia meridionalis, Zonocostites ramonae*), further supporting a nearshore depositional environment.

SPT Value Analysis

Supporting information for understanding land subsidence potential arising from the geological feature of the summary of the upper Damar Formation will be provided. The Standard Penetration Test (SPT) was performed on the Genuk (GNK) borehole to determine soil penetration resistance param. This test aimed to assess whether the dynamic resistance of the soil or sampling was affected by the pounding technique. The geotechnical black and green clay characteristics with N-SPT of Genuk (GNK) borehole samples are compared to A. Yani Airport Semarang City (TBHJ), and Tugu (KRY) of N-SPT value, (Figure 15).

The N-SPT results from the Genuk (GNK) borehole indicate that soft soil (N-SPT < 5 (soft)) is present to a depth of approximately 30 m, while firmer layers (N-SPT= 5-27) are found below. Comparable soft soil thicknesses, approximately 10-15 m, were identified along the Kendal-Semarang Coastal Plain, as observed at The Tugu



Element	(keV)	masss%	Eror%	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	Al_2O_3	19.95	3.17	19.0330	
Si K	1.739	29.76	0.40	70.17	SiO_2	63.67	8.59	55.9614	
K K	3.312	1.29	0.38	1.09	K_2O	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	10.96	1.37	9.84	FeO	10.67	1.20	16.7230	
Total		100.00		100.00		100.00	13.96		

Figure 8. The SEM microphotograph displays a clay mineral that is predominantly kaolinite, sourced from the Kendal area (KND-1).

(KRY) and A. Yani Airport (TBHJ) sites, which are composed mainly of non-cohesive soils. The thickness of the soft soil in this area is influenced by the distance to the source rock of the Damar Formation in the southern coastal plain (Figures 2 and 4).

The black and grey clay units of the Upper Damar Formation, underlying The Holocene alluvium, are characterized by N-SPT values ranging from 5 to 27 on the scale (firm to very stiff). However, at 16.70 m in GNK-1, the value is less than 5 (soft, unconfined compressive strength), suggesting the presence of unconsolidated soft clay (Figure 15). The study assumed that the Upper Damar Formation is still susceptible to further compaction due to increased effective stress from loading or excess pore water pressure, particularly under intensive groundwater extraction.

The examination of the compressibility index (Cc) at the three drill sites, Genuk (GNK), A. Yani Airport (TBHJ), and Tugu (KRY) (Figure 16), indicates a substantial potential for consolidation throughout the subsurface profile. The Cc values are classified as high to very high in the shallowest interval (0-10 m), attaining very high levels at an intermediate depth (10-20 m), and maintaining high levels throughout the deeper zone (20-48 m). The consistent high Cc across several strata indicates the inherent vulnerability of the local soils to considerable volumetric strain, affirming a major potential for consolidation settlement and greatly influencing the observed land subsidence in the region.

Figure 9. Deep file benchmark monitoring of Genuk Site with different depths, *i.e.* 85 m and 37 m. In nine months (December 2024 to September 2025), they have shown the value of subsidence until 85 m depth approximately 6.122 cm. (See table 3).

Figure 10. Deep file benchmark monitoring of Tugu Site with different depths, *i.e.* 125 m, and 20 m. In ten months (November 2024–September 2025), they have shown the value of subsidence until 125 m depth approximately 1.606 cm.

Tabel 1. Range of Compressibility of Fine Soils

Soil Type	Range (C_c)	Degree of compressibility
Soft clay	Over 0.3	Very high
Clay	0.3-0.15	High
Silt	0.15-o.075	Medium
Sandy clay	Less than 0.075	Low

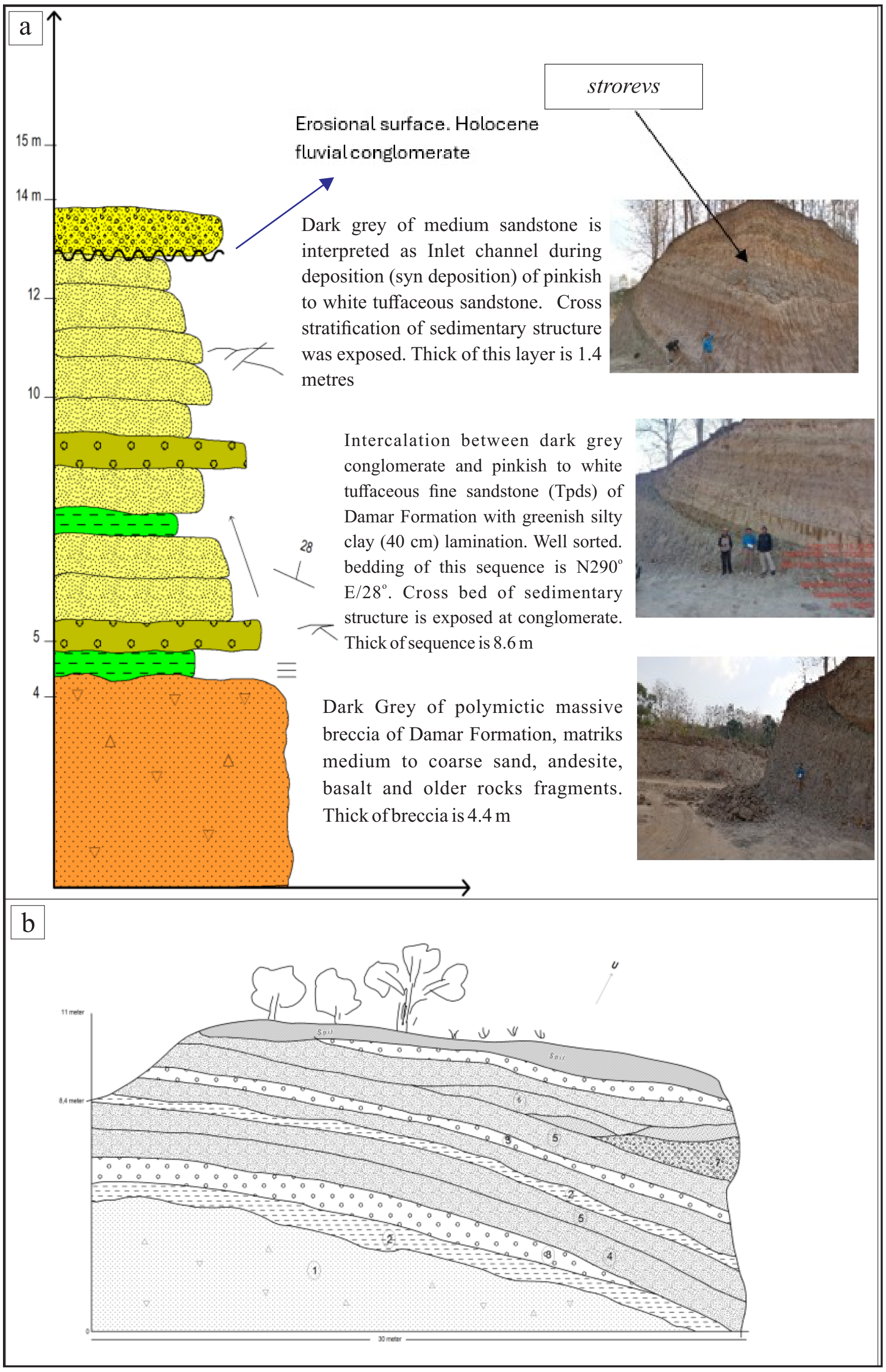


Figure 11. The measured stratigraphic section of the Damar Formation; (a) and the plan of the outcrop sequence; (b) at the Winong Quarry Site in Kendal District. The sequence is part of the lower to middle of the Damar Formation and interpreted as a fluvial environment. The thickness is approximately 16 m.

Figure 12. The outcrop of tuffaceous sandstone and conglomerate is located within the Damar Formation at the Kali Aji site (see Figure 3 for the specific locality). (a) Whole outcrop quarry mining showing dip direction to northwest (NW). (b) Tuffaceous sandstone is the lower part of the Damar Formation. (c) Base conglomerate separated lava breccia overlying tuffaceous sandstone.

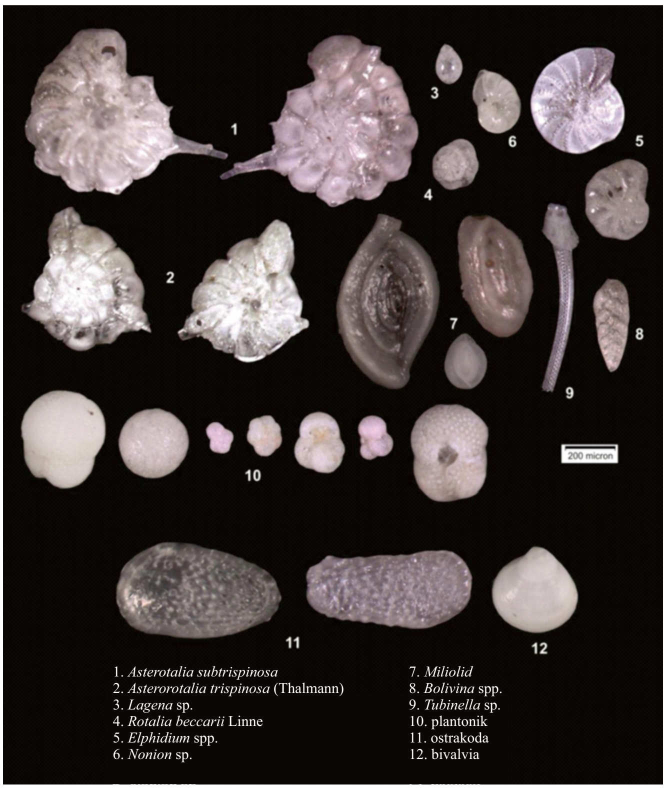


Figure 13. Abundant foraminifera fossils were deduced from the borehole of GNK-1, located at a depth of 16.50 m at the Genuk site. The occurrence of *Globigerinoides ruber* is assigned from Pliocene to Pleistocene, with an age equivalent to N18-N23 (Blow, 1969).

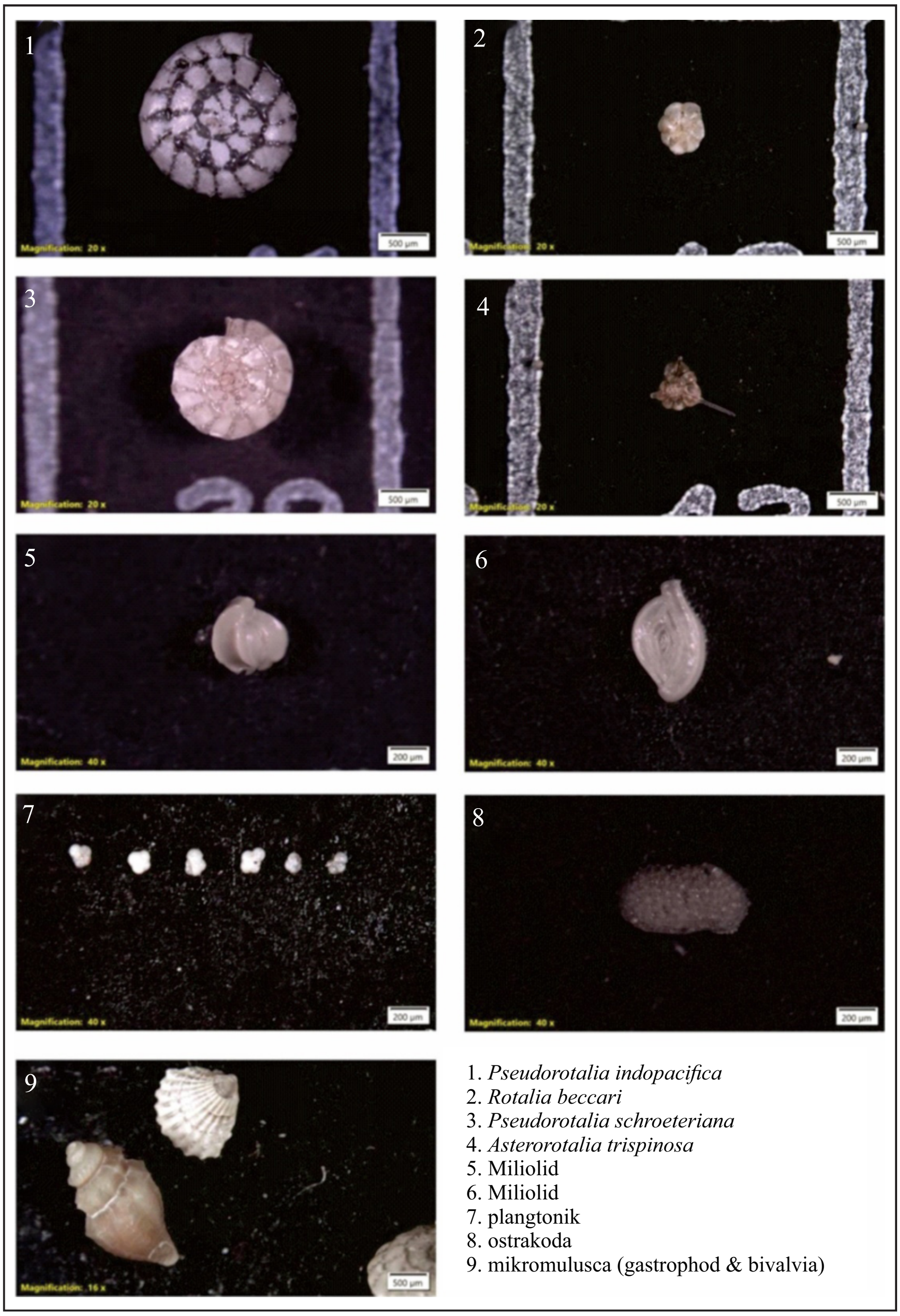


Figure 14. Abundant foraminifera fossils that were deduced from the GNK-5 borehole at a depth of 79.70 m, located at the Genuk site. The occurrence of the index fossils of *Globorotalia acostaensis acostaensis* and *Pseudorotalia indopacifica* (Thalmann) is confirmed at the base of the N21 zone until the upper zone of N21 (Late Pliocene).

The deep pile benchmark data validate the variations in compaction observed across the sites (Table 3). Genuk (GNK) (Dec. 2024-Sep. 2025) demonstrated the greatest overall compaction (6.122 cm to 85 m), with a pronounced strain escalation beneath 37 m. Conversely, Tugu (KRY) (Nov. 2024-Sep. 2025) exhibited negligible variation between its shallow (1.379 cm at 0-20 m) and deep (1.606 cm at 0-125 m) measurements, indicating restricted compressibility at increased depths. The most profound profile at A. Yani Airport (TBHJ) from January 2025 to September 2025 recorded 2.819 cm of cumulative compaction over a distance of 295.6 m.

Table 2. Foraminifera and Pollen Analysis at Genuk Borehole

No	Sample Code	Pollen	Spora	Foraminifera
1	GNK-1	*Chenopodipollis spp.* (Chenopodiaceae.) *Florschuetzia levipoli* (Lythraceae) *Betula sp*.(Betulaceae.) *Celtis sp*.(Cannabaceae) *Echitricolpolites spinosus* (Compositae) *Castanopsis sp*.(Fagaceae) *Engelhardia sp*.(Juglandaceae) Euphorbiaceae Leguminosae *Monoporites annulatus* (Gramineae) *Mallotus sp.* (Euphorbiaceae) Meliaceae *Pinus pollenites type* (Pinaceae) *Tilia sp*.(Malvaceae) *Elaeocarpus sp*.(Elaeocarpaceae) *Zonocostites ramonae* (*Rhizophora type*,Rhizophoraceae) *Randia sp*.(Rubiaceae) Rubiaceae Utricaceae	*Cyathea sp*.(Cyatheaceae) *Laevigatosporites* (Polypodiaceae) *Polypodium spp.* (Polypodiaceae) *Verrucatosporites usmensis*(Polypodiaceae) *Pteris spp*.(Pteridaceae)	**Planktonic Foraminifera :** *Globigerinoides trilobus immaturus* LeRoy *Orbulina universa* d'Orbigny *Globorotalia acostaensis acostaensis* Blow *Globorotalia sp.* *Globigerinoides bulloideus* Crescenti *Globigerinoides sp.* *Globigerinoides ruber* (d'Orbigny) **Small Bentonic Foraminifera :** *Asterorotalia subtrispinosa* *Asterorotalia trispinosa* (Thalmann) *Lagena sp.* *Rotalia beccarii* Linné *Elphidium discoidale* (d'Orbigny) *Nonion spp.* *Elphidium advenum* Cushman *Bolivina spp.* *Spiroloculina communis* Cushman and Todd *Quenqueloculina compta* Cusman *Tubinella sp.* (sangat melimpah) **Large Bentonic Foraminifera :---** **Other Fossils :** ostrakoda micro mollusca (bivalvia dan gastropoda) biota fragment
2	GNK-3	*Celtis sp.* *Elaeocarpus sp.(Elaeocarpaceae)* *Engelhardia sp.(Juglandaceae)* *Moraceae* *Monoporites annulatus (Gramineae)* *Tilia sp. (Malvaceae)* *Shorea sp.(Dipterocarpaceae)*	*Pteris spp.(Pteridaceae)* *Polypodium spp. (Polypodiaceae)*	No foraminifera
3	GNK-4	*Polvadovellenites vancompei* (*Acacia type ,Leguminosae*) *Elaeocarpus sp*.(Elaeocarpaceae) Euphorbiaceae *Florschuetzia meridionalis*(Lythraceae) *Monoporites annulatus* (Gramineae) *Mallotus sp.* (Euphorbiaceae) Meliaceae Moraceae *Palmapollenitas* Rubiaceae *Zonocostites ramonae* (*Rhizophora type*,Rhizophoraceae)	*Cyathea sp*.(Cyatheaceae) *Laevigatosporites* (Polypodiaceae) *Verrucatosporites usmensis*(Polypodiaceae) *Pteris spp*.(Pteridaceae)	
4	GNK-5	No Palynomorph		**Planktonic Foraminifera :** *Globorotalia spp.* *Globigerinoides bulloideus Crescenti* *Globorotalia acostaensis acostaensis* Blow *Globigerinoides spp.* Indeterminate fossil **Small Bentonic Foraminifera :** *Pseudorotalia schroteriana* (Parker & Jones) *Pseudorotalia indopacifica* (Thalmann) *Rotalia beccarii* Linné *Asterorotalia trispinosa* (Thalmann) *Asterotalia subtrispinosa* *Spiroloculina communis* Cushman and Todd *Spiroloculina robusta* Brady *Triloculinella sublineata* Brady *Elphidium advenum* Cushman *Quenqueloculina spp.* *Elphidium sp.* *Bolivina sp.* *Nodosaria sp.* *Eggerella bradyi* (Chusman) *Tubinella sp.* **Large Bentonic Foraminifera :---** **Other Fossils :** ostracoda micro mollusca (bivalvia dan gastropoda)

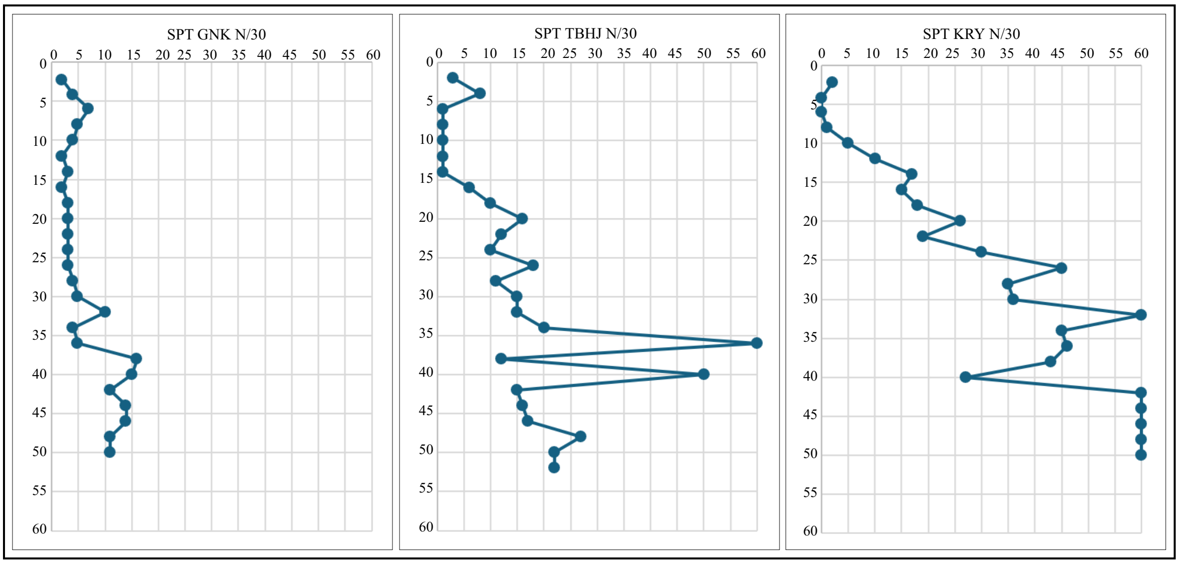


Figure 15. The Standard Penetration Test value (SPT) of alluvial and the Upper Damar Formation from bore holes Genuk (GNK), A. Yani Airport (TBHJ) and Tugu (KRY) Sites.

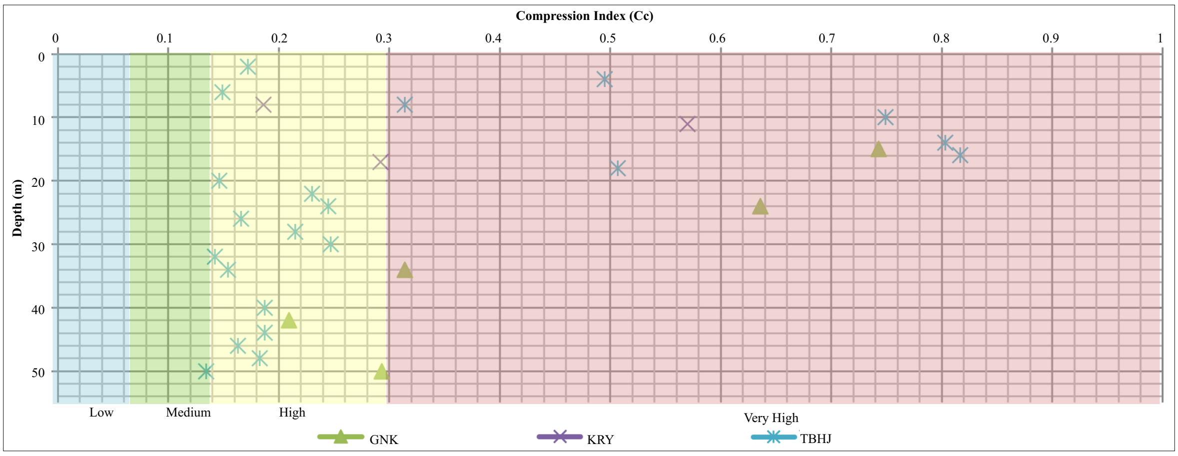


Figure 16. Compression Index Values of Cohesive Soil from bore holes Genuk (GNK), A. Yani Airport (TBHJ) and Tugu (KRY) Sites.

Table 3. Deep Pile Benchmark Subsidence Monitoring at Genuk, Tugu and A.Yani Airport Subdistricts

Deep pile benchmark	Depth (metres)	Indication of compaction (cm), November 2024 until September 2025
Genuk (GNK)	0 - 37	2.047
	0 - 85	6.122
Tugu (KRY)	0-20	1.379
	0-125	1.606
A Yani Airport (TBHJ)	0-295,6	2.819

Scanning Electron Microscope (SEM) Analysis

SEM observations revealed consistent mineralogical composition across the samples, dominated by quartz, feldspar, and clay minerals such as illite, a mixed-layer clay of illite-smectite, and kaolinite, (GNK-4, GNK-7, and GNK-9). The presence of illite-smectite in the Upper Damar Formation suggests varying diagenetic conditions relative to the lower units. Smectite (*e.g.* montmorillonite), in particular, is highly expansive due to its ability to absorb water and exchange cations (Na^+, Ca^{2+}) within interlayer spaces. Illite is less expansive due to potassium interlayers, which inhibit swelling. The predominance of illite-smectite in GNK samples indicates a moderate to high potential for compression and settlement under wet conditions (Figures 5, 6, and 7).

SEM observations revealed a consistent mineralogical composition across all samples, primarily dominated by quartz, feldspar, and various clay minerals such as kaolinite, illite, and a mixed-layer clay mineral of illite-smectite. The presence of illite-smectite in the Upper Damar Formation suggests that the diagenetic conditions during and after deposition were variable, with differences in pore fluid composition, temperature, and pressure influencing mineral stability and alteration (Bjorlykke, 1998 and Wafid *et al.,* 2025).

Smectite, for example, such as montmorillonite, is highly expansive due to its ability to absorb water and exchange cations like Na^+ and Ca^{2+} within its interlayer spaces. According to Chen (1975), this expansiveness can lead to significant volume changes, which have implications for soil stability and compaction potential, especially under wet conditions. Conversely, illite structure contains potassium ions in the interlayer spaces, which greatly inhibit swelling, making it less expansive and more stable in moist environments.

This mineralogical assemblage suggests that the clay-rich layers in the Upper Damar Formation at Genuk Area (GNK- 4, 7, and 9) may undergo considerable volumetric change over time, contributing to land subsidence, especially in areas experiencing groundwater exploitation or other pore water pressure variations than Kendal (KND-1), whereas dominated by kaolinite (Figure 8). Overall, these mineralogical characteristics highlight the importance of considering diagenetic mineral transformations when assessing geotechnical stability and land subsidence risks in the region (Chen, 1975; Nelson and Miller, 1992).

Discussion

Stratigraphic Architecture of The Upper Damar Formation and Its Depositional Environment

Land subsidence in the Kendal and Semarang areas was studied based on detailed stratigraphy and sedimentology of the Damar Formation, which underlies the Holocene alluvial and overlies the Kerek Formation, on the basis of stratigraphic profiling, sedimentological interpretation, and monitoring data from deep pile benchmarks in Semarang and Kendal Cities.

To begin with, the stratigraphy and sedimentology of the Damar Formation consist of three members, and each member has a typical characteristic depositional environment from marine to fluvial (Figure 17), which are:

a. Lower Member of the Damar Formation is characterized by interfingering between breccia and tuffaceous sandstone, and is typically a volcanic deposit within a distal facies in the intra-arc basin.
b. Middle Member 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.
c. Upper Member is predominantly of black and green clay, which is rich in foraminifera, pollen, and marine mollusks, indicating an open marine to pro delta depositional environment.

The volcanic deposits, such as tuffaceous sandstone, conglomerate, medium to fine-sandstone, and polymictic breccia in the middle and lower parts of the Damar Formation, are probably derived from reworked products of the Miocene volcanic arcs, possibly correlated to the Old Andesitic Formation (OAF) in Semarang and the southern Kendal (Figure 2).

This is probably due to the relationship between Kendal and Semarang and the former accommodation space of the foreland basin during the Pliocene, which is a more distal facies. The deposition of the middle and lower Damar Formation is interpreted as an upper delta plain environ-

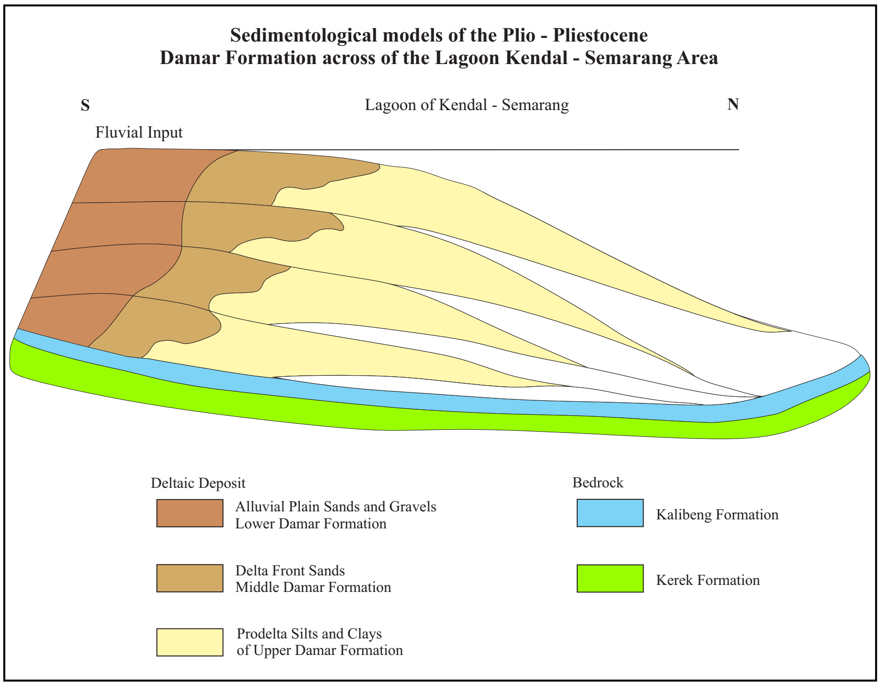


Figure 17. A new interpretation sedimentological model of the Post Miocene/Pliocene to Holocene Kendal-Semarang region.

ment with a fluviatile-dominated delta rather than tidal influence. The formation is characterized by features such as commonly fining upward layers, cross-bedding, ripple cross-stratification, scour surfaces, and clay lenses that are exposed in Winong Quarry and Kali Aji (Figures 11 and 12).

During the Late Pliocene to Pleistocene where the Upper of Damar Formation was deposited, the studied area gradually changed from the upper deltaic plain environment to tidal influence of pro delta setting (Allen *et al.*, 1976; Galloway, 1983). This is evidenced by coarsening upwards sequences, dominant clay deposit with the presence of abundant marine microfossils, from neritic to close mangrove and decreasing fluvial influence (Figure 17).

At the Winong Village section (Kendal), features concern the sedimentary structures of sandstone body within ribbon (Figure 11) which are separated by scoured surfaces called stories-scour, the internal structures of the stories are cross-stratification (curved foreset, scoop erosional based, or planar). According to Friend *et al.* (1979), this body is interpreted as the result of a single sedimentation, during which the channel was plugged by sand transported at the high stage as mega ripples, and spilled laterally a few meter on the overbank area, which mainly accumulated deposits of silt grade. This study assumed that the lower and middle Damar Formation may reflect a low or high flow strength, strong banks, a flash flooding regime, and differential vertical movement of the alluvial area relative to the same base erosion (Figures 3, 12, and 18).

During the Quaternary, especially from the Pleistocene to Early Holocene, marine transgression over she Sunda Shelf resulted in widespread deposition of thick clay and peat sequences in the deltaic areas across Southeast Asia, varying from 10 - 40 m (Cox, 1970). The uppermost layers of the Damar Formations were possibly deposited during a Maximum Flooding Surface (MFS), characterized by the peak abundance and diversity of planktonic and benthic foraminifera as well as marine to mangrove-associated palynomorphs.

Clastic green and black clay of the Upper Damar Formation observed in the Damar River, and Genuk borehole, conformably overlies older volcanic deposits of the Damar Formation (Middle and Lower sequences). Biostratigraphic data also confirm their deposition within the N 18 - N23 zones, from

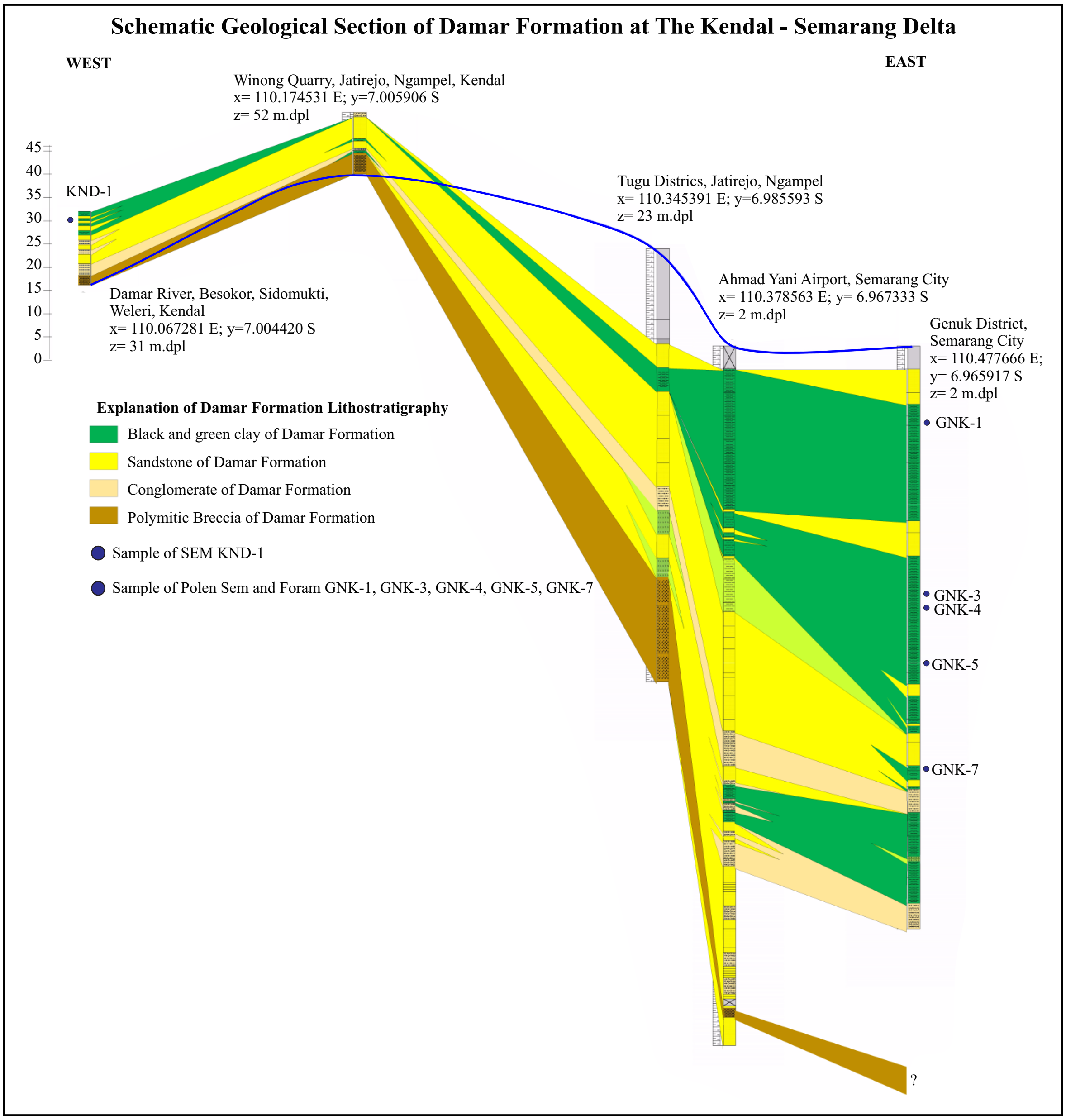


Figure 18. A new interpretation of schematic geological section across the Kendal-Semarang deduced from the field-measured section at Damar River and bore holes of Genuk, Tugu Karanganyar, A. Yani Airport, and Tugu Sites.

Pliocene to Pleistocene (Figure 13). These deltaic black and green clays of the Upper Damar Formation exhibit high compressibility, making them a significant contributor to modern land subsidence in the studied area (Figures 15, 16, and 17).

Land Subsidence Correlated with Stratigraphic Architecture and The Geotechnical Parameter of The Upper Damar Formation

The stratigraphy of the Upper Damar Formation is composed predominantly of black and green clay with organic-rich silty clays, which plays a critical role in the ongoing land subsidence observed in Kendal-Semarang. These facies are highly compressible and are often rich in microfossils such as pollen and molluscan bioclasts.

Scanning Electron Microscope (SEM) analysis confirms that these clays are composed of expansive minerals such as illite, smectite, and mixed-layer clay of illite-smectite. Smectite, in particular, has a high-water absorption capacity due to the presence of exchangeable Na^+ and Ca^{2+} cations in its interlayer spaces (Figures 13 and 14). When saturated, these clays experience a reduction in shear strength, increasing their susceptibility to collapse and settlement. Illite also exhibits some expansiveness, though to a lesser extent, due to the stabilizing presence of K^+ ions, which inhibit interlayer swelling (Chen, 1975; Tiwari and Dhungana, 2009).

In the Genuk area, samples GNK-4, GNK-7, and GNK-9 (Figures 5 to 7) show a predominance of mixed-layer clay of illite-smectite, suggesting that the area remains prone to further compression. Consequently, the Genuk is considered more susceptible to land subsidence than Kendal, where kaolinite is a less expansive clay and appears more dominant.

In-situ Standard Penetration Test (SPT) results further support this interpretation. Coastal sites in Kendal and Semarang exhibit soft soils (N-SPT < 5) within the upper 10-20 m (Figure 11), commonly associated with Holocene alluvial deposits. Notably, the Genuk (GNK) site exhibits soft soil conditions to depths exceeding 30 m, indicating the presence of deeper compressible layers within The Upper Damar Formation (Figure 15).

Furthermore, cohesive soils with N-SPT values <15, indicating susceptibility to primary consolidation, extend to depths of up to 50 m in Genuk (GNK) and A. Yani Airport (TBHJ) sites. Consolidation tests confirm relatively high compression index (Cc) values in boreholes at Genuk (GNK), A. Yani Airport (TBHJ), and Tugu (KRY), suggesting significant settlement potential under structural or overburden loading (Figure 16).

More recent monitoring data from the deep pile benchmarks confirms active subsidence. at A. Yani Airport (TBHJ) from January 1st to September 2025 and Genuk (GNK), monitoring from December 2024 to September 2025 recorded the average annual subsidence rates of 2.819 cm and 6.122 cm, respectively. Furthermore, benchmarks at Tugu, Karanganyar, monitored until September 2025, also recorded measurable subsidence rate 1.606 cm (Table 3).

These results indicate that compression is not limited to near-surface Holocene soils, but also includes the deeper clay-rich layers of the Upper Damar Formation (Tables 2 to 3 and Figure 16). A. Yani Airport (TBHJ) subsidence is primarily concentrated in the 30-88 m layers. Similarly, Genuk (GNK) shows dominant compaction in the upper 30-88 m interval, despite being closer to the coastline. These findings emphasize that both shallow alluvial and deeper soft-rock formations contribute to ground settlement.

Near-surface subsidence can occur suddenly, often triggered by increased pore pressure from leaking pipes or groundwater withdrawal (Ali and Choi, 2020; Tichavsky *et al*., 2020). Additionally, Sarah *et al.* (2018, 2020, 2021) demonstrate that porewater dissipation occurs more rapidly in saline clay than in freshwater clay, attributed to increased hydraulic conductivity, which leads to expedited consolidation and a higher rate of subsidence. Analysis of foraminiferal and palynomorph assemblages, along with Scanning Electron Microscope (SEM) data from well-log analyses of the Genuk and Tugu boreholes, indicates that the black and green clay of the Upper Damar Formation is associated with brackish to saline clay rather than freshwater clay.

Mention above, the combined Foraminifera, Pollen, SEM, geotechnical, and benchmark data presented here reveal that deeper geological units, including Pliocene-Pleistocene clays of the Upper Damar Formation, are also significant contributors to land subsidence in the Kendal-Semarang area.

The integration of these techniques advances and facilitates the study of land subsidence in Semarang through the application of the InSAR method (Aditiya *et al*. 2023, Janur *et al*., 2025).

Conclusions

The depositional history of the Damar Formation in Kendal and Semarang demonstrates a distinct transition from fluvially dominated upper delta plain depositional environments in the middle and lower members to a tidally influenced prodelta setting during the Upper Damar Formation, spanning the Late Pliocene to Pleistocene. This study proposes a geotechnical and stratigraphic-based method for assessing land subsidence risk in the coastal zones of Kendal and Semarang. Key findings include:

- Land subsidence in the studied area is influenced not only by groundwater extraction at shallow Holocene soils, but also natural compaction. However, the deeper clay layers (*e.g.* smectite and illite) of the Upper Damar Formation, which can consolidate further when pore pressures are reduced by pumping.
- Based on foraminiferal and palynomorph assemblages, along with Scanning Electron Microscope (SEM) data from well-log analyses of the Genuk and Tugu boreholes, indicates that the black and green clay of The Upper Damar Formation is associated with brackish to saline clay rather than freshwater clay and contribute significantly to long-term subsidence, when pore pressure and loading are reduced by groundwater extraction.
- The black and grey clay units of the Upper Damar Formation, underlying the Holocene alluvium, are characterized by N-SPT values ranging from 5 to 27 on the scale (firm to very stiff). However, at 16.70 m in GNK-1, the value is less than 5 (soft, unconfined compressive strength), suggesting the presence of unconsolidated soft clay.
- Geotechnical parameters, including SPT and consolidation data, indicate subsidence potential extending to depths 30-88 m, particularly in Genuk (GNK) and A. Yani Airport (TBHJ).
- Deep pile benchmark monitoring confirms ongoing compaction within both shallow and deep subsurface layers.

In conclusion, these findings highlight the essential necessity of employing an interdisciplinary approach that amalgamates stratigraphic, geological, and geotechnical data for the precise evaluation and management of land subsidence risks in the deltaic and coastal areas of Central Java Province. Moreover, we suggest augment the quantity and geographical distribution of subsidence monitoring. Augment the quantity and geographical distribution of subsidence monitoring augment the quantity and geographical distribution of subsidence monitoringAugment the quantity and geographical distribution of subsidence monitoring stations. Denhanced subsidence monitoring stations, integrated with a groundwater monitoring well, extending to lithology unaffected by compaction.

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