Facies Analysis and Depositional Environmental Interpretation of The Upper Oligocene, Block 09-2/10, Cuu Long Basin

Muoi Duy NGUYEN[1,2)]*, *Anh Ngoc LE*[1,2)], *Hoa Minh NGUYEN*[1,2)], *Ngan Thi BUI*[1,2)]

[1)] Petroleum Geology Department, Faculty of Petroleum and Energy, Ha Noi University of Mining and Geology, 18 Vien Street – Duc Thang Ward – Bac Tu Liem District – Ha Noi – Vietnam

[2)] Basin, stratigraphy and sedimentary process group (BSSP), Ha Noi University of Mining and Geology, 18 Vien Street – Duc Thang Ward – Bac Tu Liem District – Ha Noi – Vietnam

* Correspondence: nguyenduymuoi@humg.edu.vn

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Abstract

The article presents the facies and environment of the Upper Oligocene sediments in the area of block 09-2/10 based on the analysis of seismic facies and well data of the neighboring areas. The results of the interpretation of seismic data indicate that the upper Oligocene sediments are limited by the top C, top D seismic reflectors. The environment is formed from lagoons, lakes to deep lakes. Seismological facies analysis identified 03 facies including seismic facies with medium to poor reflection amplitude, medium continuous, low frequency reflecting the lacustrine sediments (80%) in most of the lake center. Strong reflective seismic facies, sigmoidal clinoforms reflect the lakeside sediments (15%) distributed in the lakeside shelf. The seismic facies with average and continuous amplitude poorly reflect alluvial sediments (5%) in the Northwest region. The direction of sediment transport is mainly from the Northwest and Southwest in the area. The sandstone sequences are distributed on the slopes of the lake and the lake bottom, which is potential reservoir.

Keywords: *Cuu Long basin, upper oligocene, depositional environment, seismic facies, block 09-2/10*

1. Introduction

The Cuu Long Basin is one of the most detailed drilled and studied basins in the continental shelf of Vietnam. This basin is covered by a large volume of seismic profiles as well as many oils and gas exploration and production wells. The basin's sedimentary fill is dominated by Cenozoic sediments, with the Oligocene and Lower Miocene formations serving as the primary targets for hydrocarbon exploration and exploitation. These sediments are characterized by a diversity of depositional environments, including fluvial, lacustrine, peat swamp, brackish lagoon, and inner neritic settings.

Block 09-2/10 is located in the center of Cuu Long basin, Vietnam (Figure 1). Around the study area are large oil and gas fields such as Bach Ho, Te Giac, and Rang Dong. However, oil and gas research and exploration activities in 09-2/10 are still limited. In addition, in the study area, seismic explosion collection and drilling of an exploratory well have been carried out in the Middle Miocene sediments. The Lower Miocene sediments are not capable of generating hydrocarbons. Therefore, Oligocene sediments are the main study object for this paper. The deposition conditions of Upper Oligocene C are unclarified. The paper shows sedimentary facies and depositional paleoenvironment of the Upper Oligocene C based on analysis of seismic facies and well around block 09-2/10.

2. Geological setting

Cuu Long basin is a Cenozoic rift basin located in the Southeastern shelf of Vietnam. The geological evolution of the Cuu Long basin is divided into three periods: pre-rift, syn-rift and post-rift (Figure 2).

Pre-rift, especially from the Jurassic to Paleocene, is the period of formation and uplift of extrusive magmatic basement.

Syn-rift: This period commenced at the end of the Eocene - Early Oligocene under the influence of aforementioned tectonic events with the main extension direction being the NW-SE.

Post-rift: Near the end of the Early Miocene, the NW-SE East Sea spreading weakened, quickly terminated (17 Ma), and was immediately followed by crustal cooling period. Post-rift sediments were common in that they were all widely distributed, undisplaced, unfolded, and almost horizontal.

The stratigraphy of block 09-2/10 in the Cuu Long basin consists of Pre-Cenozoic basement and Cenozoic sedimentary cover. The characteristics of lithology and fossil assemblages of each formation unit are summarized in the generalized stratigraphic column of the basin (Fig 3). Pre-Paleogene basement: The Pre-Paleogene basement in the Cuu Long basin is composed of mostly magnetic intrusive rocks with main lithologies of granite, granite - gneiss, granodiorite, diorite, adamellite, monzodiorite, gabbro, monzogabbro. The metamorphic rocks are also encountered in some places [6].

Lower Tra Tan – Tra Cu formation – Oligocene E: This continental sediment consists of shale, siltstone and sandstone, which were deposited unconformably on the Pre-Paleogene basement. It is distributed widely across the southeastern area and divided into two sub-units:

Oligocene E Lower in the lower part and Oligocene E Upper in the upper part. The lower one is dominated by medium – to coarse grained sandstones composed of mostly granitic fragments and feldspars, interbedded with hard organic-rich black shale layers. The other one is composed majorly of fine to medium grained sandstones interbedded with gray shale layers. In addition, magma intrusions such as dykes, composed majorly of andesite/basalt were found occasionally [7].

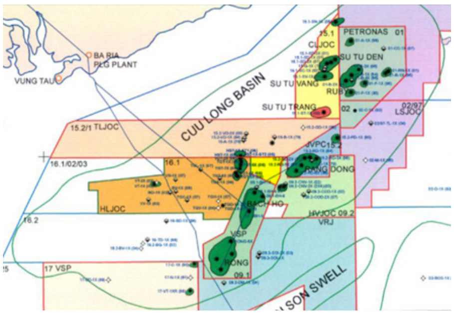


Fig. 1. Location of the study area

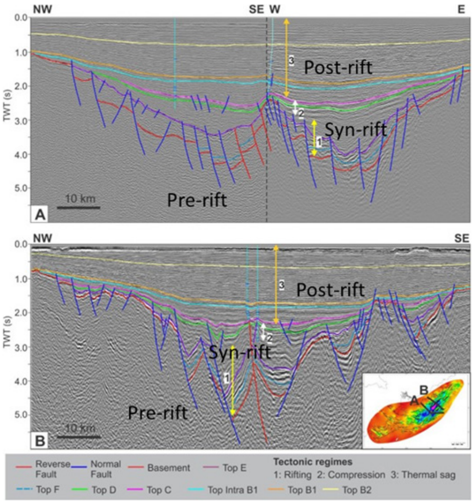


Fig. 2. The geological evolution of the Cuu Long basin (Modified after William J. Schmidt, 2018)

Upper Tra Tan Formation – Oligocene D: It is majorly organic rich brown shale deposited in lacustrine environment, occasionally interbedded with local layers of coal or sandstone. However, toward the Eastern boundary of the sub-basin (close to Con Son swell), thick layers of sandstone were deposited on top of Oligocene D shale. Upper Tra Tan Formation – Oligocene C: This section is the mixtures of fine-grained sandstones and lacustrine brown shale [6].

Bach Ho Formation – Miocene BI: This stratigraphic sequence is divided into two sub-units Miocene BI.1 (lower part) and Miocene BI.2 (upper part). Miocene BI.1 is composed mainly of sandstone dominant fluvial-deltaic deposits with small intercalation of shale deposited in floodplain or some brackish environments, while Miocene BI.2 is composed mainly of sandstone interbedded with shale/claystone, occasionally shallow marine siltstone and limestone. The top section of Miocene BI is Bach Ho shale, a thick and continuous shale layer, acting as a regional seal for the whole Cuu Long basin [6].

3. Material and methods

3.1. Materials

The seismic data used for this study is 250km2 PSTM 3D seismic cube of block 09-2/10. In addition, lithological, paleontological, and geophysical data from wells A1, A2, B1, B2, C1, C2, C3, D, E, F and G were also used to determine the environment of sediments (Figure 4). Seismic facies analysis was combined with petrographic and paleontological data to forecast the sedimentary environment of sequence C.

3.2. Methods:

Seismic facies analysis:

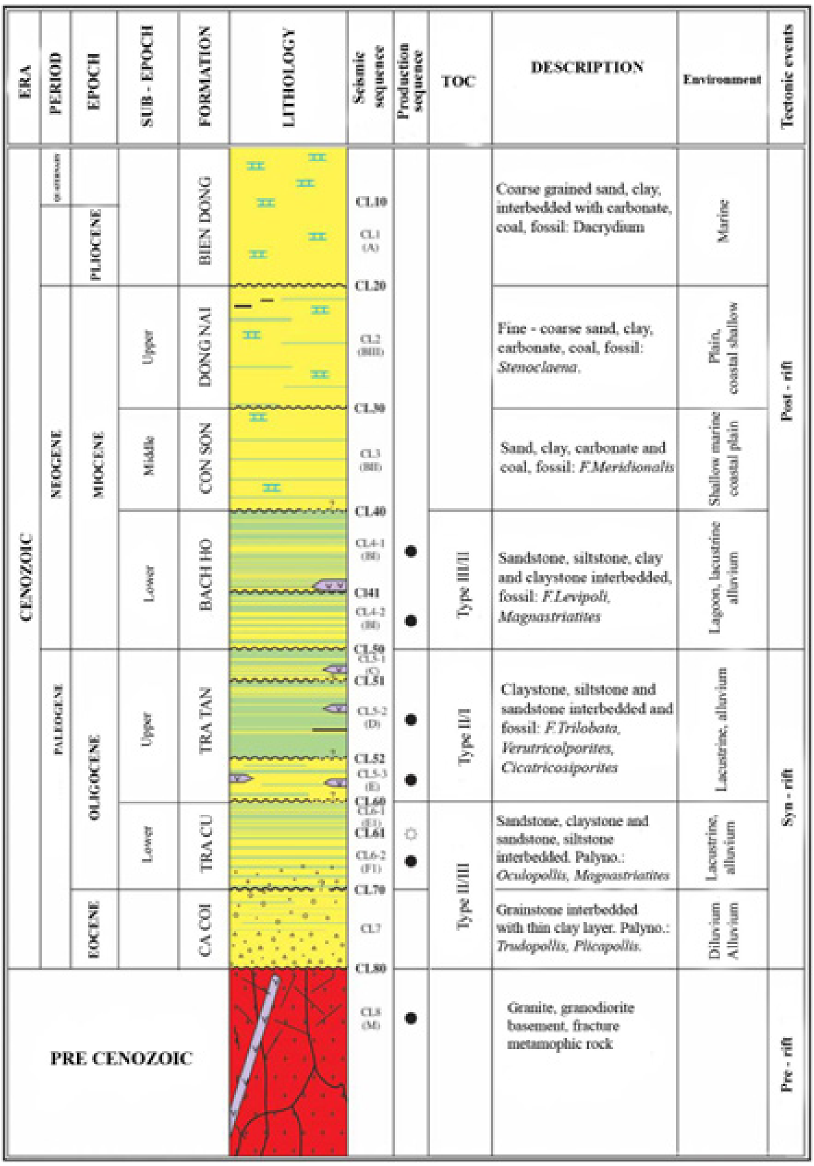
Seismic facies analysis is the description and interpretation of seismic reflection parameters, such as configuration, continuity, amplitude, and frequency, within the stratigraphic framework of a depositional sequence [1,2]. In seismic facies analysis, different seismic sequence has a different wave characteristics and is identified by the shape, amplitude, frequency, continuity of the seismic reflections. The external geometry and internal reflection of the reflected wave can reflect the deposition process as well as the direction of the source of the sedimentary material.

Log curve shape Analysis:

Based on the shape of the gamma ray curve, it is possible to determine the sedimentary environment (Figure 5). The shapes of well-log curves analysis serve as basic tool to interpret depositional facies because shape of log is directly related to the grain size of rock successions [4]. The log curve shapes were used to interpret the depositional environment, The study of core with relation to logs is also an important tool of facies interpretation in the subsurface [2].

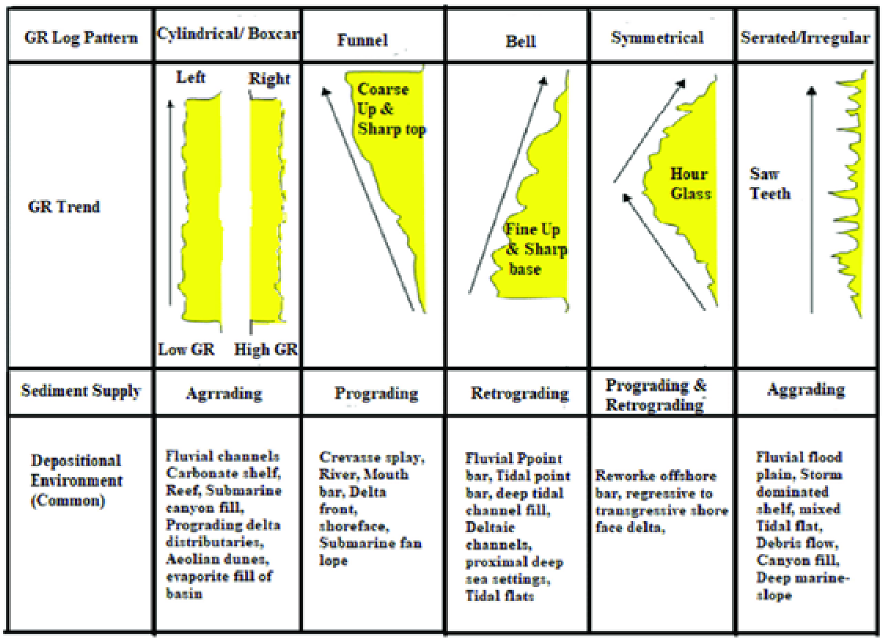
Petrographic analysis:

Petrographic analysis identifies the mineral content for classification of a rock. Analysis usually comprises the description of the macroscopic aspects of the rock, such as fabric, color, grain size, and other relevant characteristics that may be visually observed in hand specimen or in outcrops, and chiefly the identification and description of microscopic characteristics of the studied material in thin sections such



ERA	PERIOD	EPOCH	SUB - EPOCH	FORMATION	LITHOLOGY	Seismic sequence	Production sequence	TOC	DESCRIPTION	Environment	Tectonic events
CENOZOIC	QUATERNARY	PLIOCENE		BIEN DONG		CL10 CL1 (A) CL20			Coarse grained sand, clay, interbedded with carbonate, coal, fossil: Dacrydium	Marine	Post - rift
	NEOGENE	MIOCENE	Upper	DONG NAI		CL2 (BIII) CL30			Fine - coarse sand, clay, carbonate, coal, fossil: *Stenoclaena*.	Plain, coastal shallow	
			Middle	CON SON		CL3 (BII) CL40			Sand, clay, carbonate and coal, fossil: *F.Meridionalis*	Shallow marine coastal plain	
			Lower	BACH HO		CL4-1 (BI) Cl41 CL4-2 (BI) CL50	● ●	Type III/II	Sandstone, siltstone, clay and claystone interbedded, fossil: *F.Levipoli, Magnastriatites*	Lagoon, lacustrine alluvium	
	PALEOGENE	OLIGOCENE	Upper	TRA TAN		CL5-1 (C) CL51 CL5-2 (D) CL52 CL5-3 (E) CL60	● ●	Type II/I	Claystone, siltstone and sandstone interbedded and fossil: *F.Trilobata, Verutricolporites, Cicatricosisporites*	Lacustrine, alluvium	Syn - rift
			Lower	TRA CU		CL6-1 (E1) CL61 CL6-2 (F1) CL70	○ ●	Type II/III	Sandstone, claystone and sandstone, siltstone interbedded. Palyno.: *Oculopollis, Magnastriatites*	Lacustrine, alluvium	
		EOCENE		CA COI		CL7 CL80			Grainstone interbedded with thin clay layer. Palyno.: *Trudopollis, Plicapollis.*	Diluvium Alluvium	
PRE CENOZOIC						CL8 (M)	●		Granite, granodiorite basement, fracture metamophic rock		Pre - rift

Fig. 3. Generalized stratigraphy of the Cuu Long basin [3]



GR Log Pattern	Cylindrical/ Boxcar	Funnel	Bell	Symmetrical	Serated/Irregular
GR Trend	Left Right Low GR High GR	Coarse Up & Sharp top	Fine Up & Sharp base	Hour Glass	Saw Teeth
Sediment Supply	Agrrading	Prograding	Retrograding	Prograding & Retrograding	Aggrading
Depositional Environment (Common)	Fluvial channels Carbonate shelf, Reef, Submarine canyon fill, Prograding delta distributaries, Aeolian dunes, evaporite fill of basin	Crevasse splay, River, Mouth bar, Delta front, shoreface, Submarine fan lope	Fluvial Ppoint bar, Tidal point bar, deep tidal channel fill, Deltaic channels, proximal deep sea settings, Tidal flats	Reworke offshore bar, regressive to transgressive shore face delta,	Fluvial flood plain, Storm dominated shelf, mixed Tidal flat, Debris flow, Canyon fill, Deep marine-slope

Fig. 5. Common sedimentological facies associated with various gamma-ray log shapes. Modified after Cant (1992)

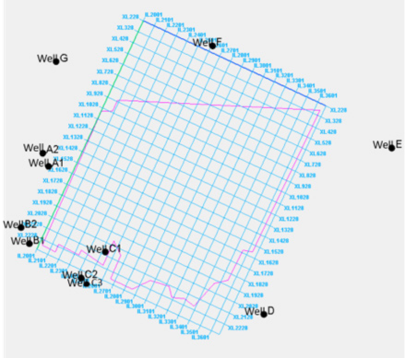


Fig. 4. A base map showing well sites relative to the seismic survey inlines and crosslines

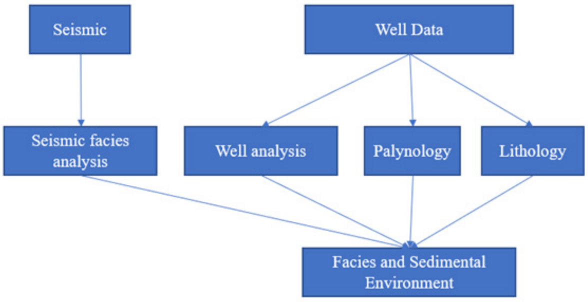


Fig. 6. The workflow for facies analysis and sediment environment study

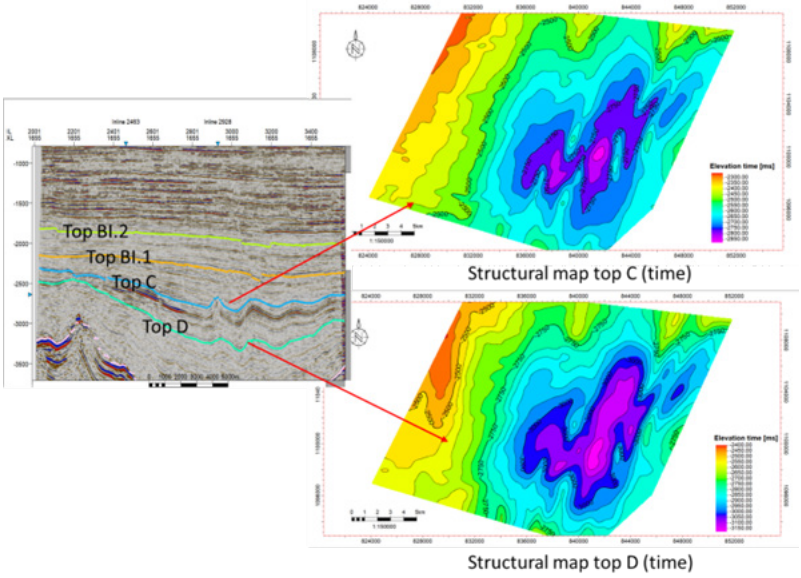


Fig. 7. The time structure map of Top C and Top D

as mineral composition, texture, grain size, and evidence of alteration and/or deformation [3]. The results of petrographic analysis are an important tool for determining the conditions of the formation of the rock.

Researching of the sedimentary environment of sequence C in the study area was carried out by the authors according to the following diagram (Figure 6).

4. Results and discussion

4. 1. Seismic interpretation

In block 09-2/10, The basement rock is deeply buried, so there is no potential structure. Therefore, seismic interpretation only focuses on the Upper Oligocene and Lower Miocene. The results of the seismic interpretation showed 4 horizons. Which are interprated including Top D (Lower Oligocene), Top C (Upper Oligocene), Top BI.1 (Lower Miocene) and Top BI.2 (Upper Miocene). The sequence C is limited by Top C and Top D (Figure 7). The structure map top C and Top D shows that this area same as subsiden. The west is a clearly an area of downslope sedimentation.

The thickness map (Figure 8a) shows the same as a deep lake. In the west, the sediment thickness is thin. In the middle, the sediment is more thicker. The models show the depositional environment and source rock deposition (Figure 8b).

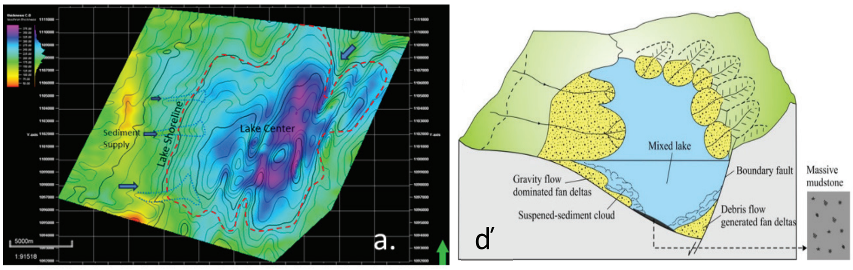


Fig. 8. a) Iso-thickness map of sequence C, b) Model of the sedimentary environment of sequence C [5]

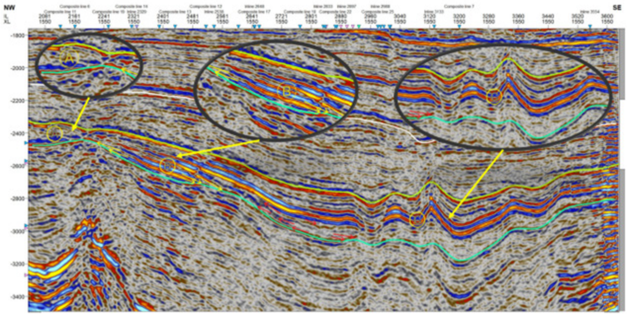


Fig. 9. Seismic section shows that sequence C has 3 main groups of reflections

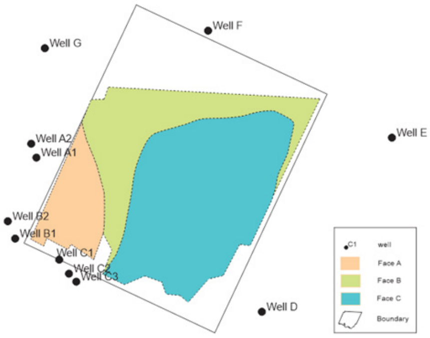
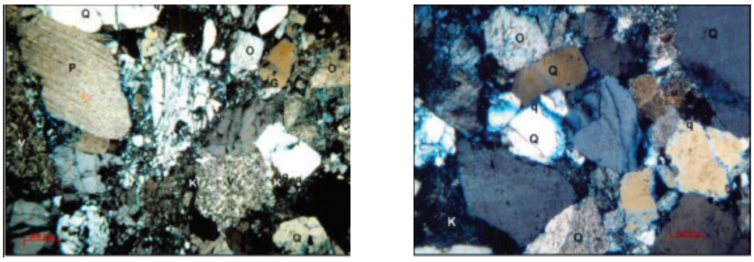
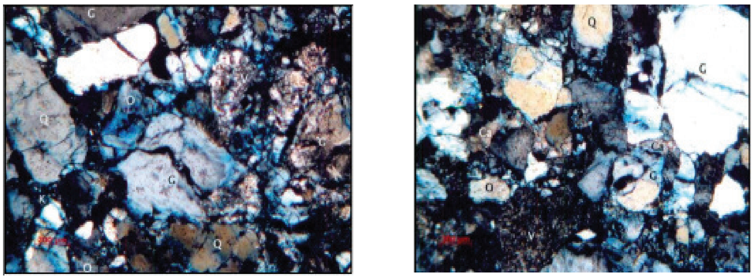


Fig. 10. Seismic facies map of sequence C



Sidewall core sample (at 3042m TVDss): arkose lithic sandstone with coarse grain, poor selectivity at well A1 (Q- quartz, P – Plagioclase)

Sidewall core sample (at 3182.5m TVDss): arkose lithic sandstone with fine grain, medium selectivity at well B1 (Q- Quartz, P – Plagioclase, k-feldspar)



Sidewall core sample (at 3012.5m TVDss): arkose sandstone with coarse grain, poor selectivity of well A2 (Q- Quartz, P – Plagioclase, k-feldspar)

Sidewall core sample (at 3026m TVDss): arkose sandstone with medium grain, poor selectivity of well A2 (Q- Quartz, P – Plagioclase, k-feldspar)

Fig. 11. Arkose sandstone of sequence C at wells A2, A1, B1 [10]

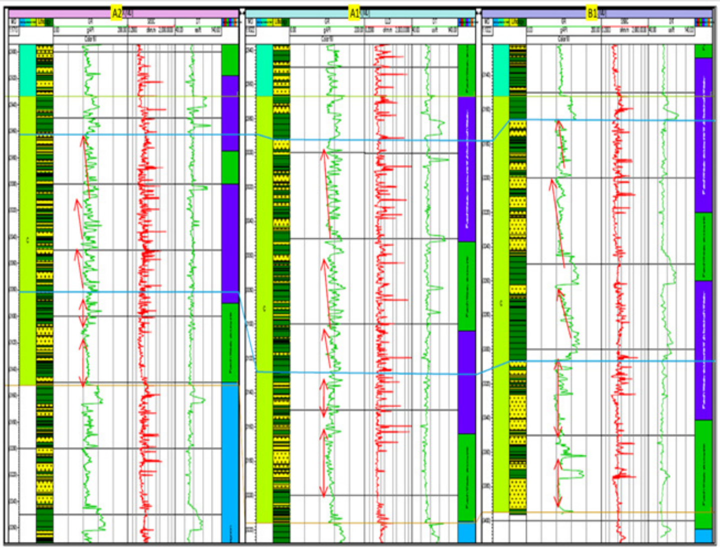


Fig. 12. Well correlation of Well A2, Well A1, Well B1

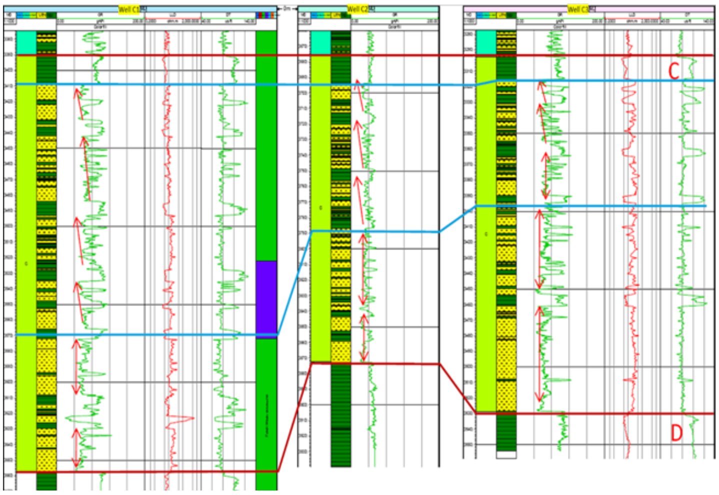


Fig. 13. Well correlation of Well C1, C2, C3

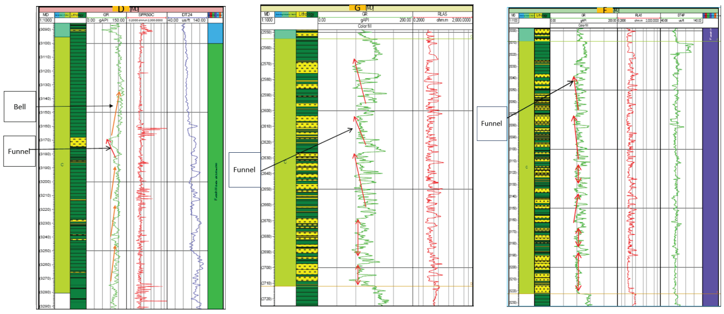


Fig. 14. Depositional environments in well area D, G, F

4.2. Seismic facies interpretation

Analyzing the seismic facies of Upper Oligocene "C" sequence, it shows that 03 seismic facies include (figure 9):

Seismic facies A shows subparallel reflection features with weak-medium amplitude, and poor continuity, reflecting medium-energy sedimentation. These seismic facies represent alluvial.

Seismic facies B has reflection with high amplitude, good continuity, and sigmoidal clinoform, which is typical for high-energy sedimentation. These facies show the shelf-slope sediments.

Facies C includes 2 groups with different characteristics. The first group is the high amplitude, good continuity, parallel reflections, shows sediments due to the change and decrease in energy gradually until completely weak. The negative phase reflections (in blue) reflect the sedimentary facies as the tails, the outermost parts of the lobe. The positive phase reflections (reddish brown) reflect the fine-grained facies of clay, formed in the period of still water, lacking sedimentary materials. The second group is a set of weak, discontinuous, chaotic. They reflect the sediment with coarser grain and poor selectivity. Which are rapidly deposited in a high-energy environment.

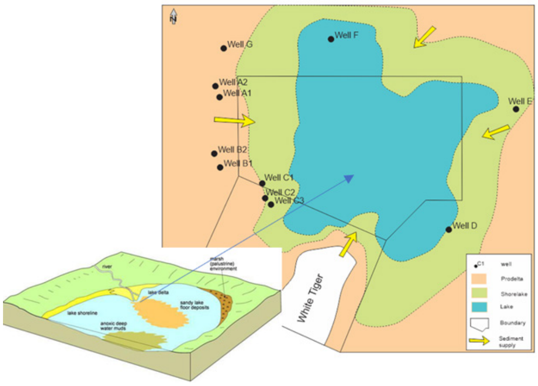


Fig. 15. Diagram of sedimentary environment of Late Oligocene (sequence C) in block 09-2/10

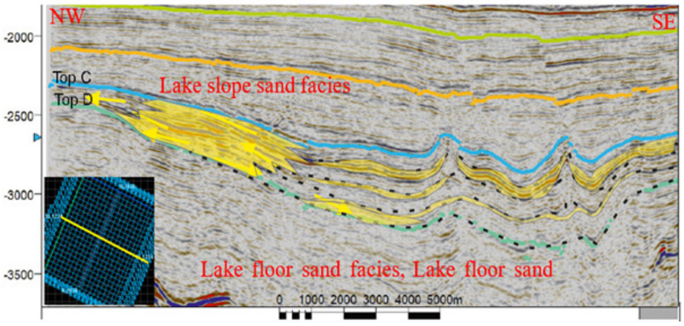


Fig. 16. Reconstruction of lake slope sand facies and lake floor sand facies

The facies C is characterized by a turbidite sedimentary, which is formed at the bottom of the lake.

The seismic facies distribution of the C sequence is shown in figure 10. Seismic facies A, distributed mainly in the western edge of the area (yellow-orange covers about 15% of the area) is characterized by discontinuous reflections. Seismic facies B have strong, continuous reflectivity (light green covers about 15% of the area) distributed in the middle of the block. Seismic facies C, which shows medium amplitude and poor continuity of reflectors, occupies most of the central part of the block (80% of the area – blue color).

4.3. The results of lithology, paleontology combined with well logging analysis

According to the results of the petrographic stratigraphy of wells A1, A2, B1, and B2, sand and clay sequences are shown. Petrographic results of thin rock slices at wells A1, A2, and B1 show arkose and sub-arkose sandstone (Figure 11), poor selectivity, and poor roundness. The sediments were formed in alluvial and pro-deltaic environments. The results of palaeontological analysis of sequence C at wells A1, A2 and B1 are mainly chalky spores and freshwater spores such as Bosedinia, showing that the sequence was formed in the fluvial and freshwater lacustrine environment [9]. The mainly block, funnel shape of the GR curve is typical for the delta environment (Figure 12).

At wells C1, C2, and C3, the sequence C includes sand layers interspersed with clay layers. Sandstone is arkose with good roundness and good sorting. The blocky and funnel shapes on GR logging curves (Figure 13) indicate the marginal lacustrine environment. The seismic expression of this sequence is characterized by medium seismic amplitude and moderate to poor continuity of reflectors, associated with marginal lacustrine sediments.

At well D, the GR log has high values and tends to be fining upward. The lithology is mainly shale layers formed under low-energy conditions can to related to the lacustrine environment. When analysis result of well G (Northwest) and well E (Northeast) also shows the lacustrine environment. The well logging analysis result of well F (Northern) indicates the marginal lacustrine environment [11] (Figure 14).

4.4. Sedimentary environment reconstruction

The Oligocene period was in the period of rifting, creating space for sediment accumulation [6,7]. Stratigraphic results of the Cuu Long Basin have shown that Oligocene sediments were formed during a period of low water level, related to river and lake environments [8,11]. The paleontological research results also clearly show a freshwater lacustrine environment [9]. Therefore, the late Oligocene sedimentary environment of block 09.2/10 can be the same. a sedimentary environment map of the Upper Oligocene was established based on the combination of the seismic facies with well data, lithology, and paleontology. On the figure 15, the center of the lake is deviated to the East, and the direction of sediment transport is mainly from the West. Delta/marginal lacustrine environments are present in most of the wells around block 09.2/10; the marginal lacustrine environment in wells A1, A2, B1, B2, C2, C3, while lacustrine environment in wells C1, D.

From the sedimentary formation model of sequence C, it is possible to reconstruct the distribution of sedimentary facies of the study area as follows:

Prograding wedge sediment has been transported towards the basin center and accumulated from the edge of the lake shelf to the slopes of the lake and can spread far into deeper water (Figure 16). Prograding wedge sediment is characterized by combinations of coarse-grain sand and grit facies with poor to moderate sorting.

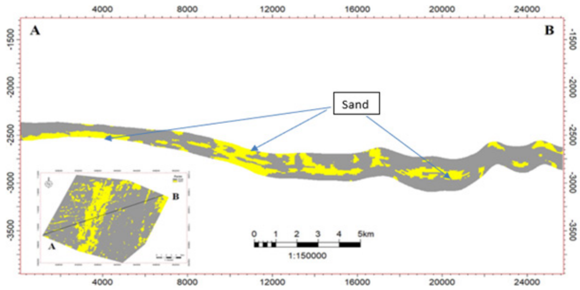


Fig. 16. Reconstruction of lake slope sand facies and lake floor sand facies

Lake floor fan sediment was formed when the lake water level was lowered, sediment was quickly transported by underground flows to the lake bottom. When dividing the facies by seismic reflection features, the distribution of sand layers has also been shown and the distribution is quite appropriate with the seismic facies model (Figure 17).

5. Conclusions

The study has clarified sedimentary facies and depositional paleoenvironment of block 09.2/10 cuu long basin in the east sea during the upper Oligocene based on the integrating of seismic facies, welllog, petrographic, and paleontology.

The results of the interpretation of seismic data indicate three facies A, B and C. The facies A are characterized by chaotic reflections, poor continuity, and low amplitudes associated with delta. The facies B is characterized by continuous seismic reflection, strong reflection amplitude, low frequency, overlapping pattern related to shelf slopes. The facies C is characterized by a weak to moderate amplitude, parallel wavy, which is related to the deep lake.

The Upper Oligocene environment was formed mainly in the lacustrine environment. The sedimentary facies include the lakeside and deep lake. The lakeside and bottom sands sequence may be potential oil and gas reservoirs.

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Identifying the Potential Application of Unmanned Aerial Vehicle Technology in Mine Waste Dumps

***Ba Dung NGUYEN*[1]**

[1] Hanoi University of Natural Resources and Environment; email: nbdung@hunre.edu.vn; ORCID: 0000-0001-5378-0926

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Abstract

In recent years, unmanned aerial vehicles (UAV) have been applied in the mining sector for a variety of purposes. This paper discusses the use of UAVs in the management of mine waste dumps based on analyzing scientific publications (January 2010 to May 2023). Three bibliography databases including Scopus, Google Scholar, and Web of Science were used to perform a thorough assessment of the literature. This study provides a comprehensive overview of UAV applications in mine waste dumps including environmental management, terrain surveying and 3D modeling, and safety and risk management. The obtained results of the study hope to give a technical reference, enhancing the understanding of UAV monitoring in mine waste dump.

Keywords: *UAV, drone, mine, mine waste dumps*

1. Introduction

The mining industry creates significant amounts of waste. According to Cebada et al. (2016), the waste produced by mining might be solid, slurry, or tailing with the most prevalent types being waste rock, tailings, slag, and tail ends. However, under certain conditions, vegetation and overburden may also be regarded as waste [1]. In mines, one of the main operations is the management of the waste dumps [2]. Mining waste is produced in all phases of mine development and extraction activities as well as technical operations related to enriching and purifying the raw material that was extracted [3]. The literature showed that there were many problems associated with mine dumps that need to be considered such as dump fires, slope stability of dumps, etc. Therefore many different methods were used and remote sensing technology seems to be used most of all. This approach can be applied in evaluating the thermal activities of a coal waste dump to detect and locate the spontaneous heating in coal dumps [4], predicting the settlement of mine waste dump [2], analyzing the stability of a mining waste dump sites [5], recognizing and extracting of a waste dump in mining area [6] studying the process of mine waste dump filling up by vegetation [7], mapping mine waste dumps in a semiarid mine district [8]. In addition, Dev and Goyal (2019) used field survey data combined with software based on Finite Difference Method to assess the waste dump slope stability at iron ore mines [9]. Based on expeditious physico-chemical parameters, Mayara et al. (2017) established the mining waste map and analyzed affected areas [10]. Some other methods were mentioned by many scientists such as geoelectrical methods for investigating mine dumps [11], a combined direct current resistivity and induced polarization approach for mapping the internal composition of a mine waste rock pile [12], geostatistical interpolation based on GIS for mapping heavy metals concentrations of mining waste dump [13], magnetometric resistivity approach for detecting preferential flow paths in mine waste rock dumps [14], geotechnical parameter method for analyzing the slope stability of mine waste dumps [15], integrating infrared thermography and close-range photogrammetry for generating a surface temperature distribution model of a coal-mining waste dump [16], application AUV for dump slope stability analysis [17], etc.

Recently, UAVs are increasingly popular tools for remote sensing applications [18]. UAVs are widely known by numerous names such as drones, unmanned aerial systems (UAS), and remotely piloted vehicles (RPVs). Thanks to recent enhancements in UAVs, this technology has secured an ever-expanding field of application in sectors like agriculture [19], construction [20], disaster management [21], transportation [22], etc. UAVs are crucial instruments in the mining sector as well. Because UAVs can be equipped with various devices such as optical, thermal, magnetic, and natural gamma-ray sensors, they can be utilized for numerous purposes like surveying and mapping [23], mine safety monitoring [24], air quality measuring [25], mine waste dumps [26], etc. There have also been many studies reviewing the application of AUVs in the mining industry. While Park and Choi (2020) reviewed academic publications on the usage of UAVs in the mine sector during three phases: exploration, exploitation, and reclamation [27], Lee and Choi (2016) mentioned the UAV technology trends and their applications in the mining industry. Like Park and Choi (2020), Loots et al. (2022) focused on the application of UAVs in the four phases (exploration, development, exploitation, and reclamation) of mining [28]. To provide information about specifications, UAV types, usage of commercially available UAVs for mine industry, requirement for the design and operation of UAVs in underground mines, Shahmoradi et al. (2020) present a thorough analysis of UAV technology and how it is used in the mining sector [29]. Ren et al. (2019) provide an overview of the various uses for UAVs and some recommendations for further advancing their use in resource development and environmental protection. In order to increase awareness and understanding of UAV uses in surveying and mapping in mine regions, Long et al. (2023) offers a technical reference that provides an overview of current advancements in the use of unmanned aerial vehicles (UAVs) for mapping and assessing surface, underground, and abandoned mines. However, all of them have not mentioned the use of this system for monitoring and man-

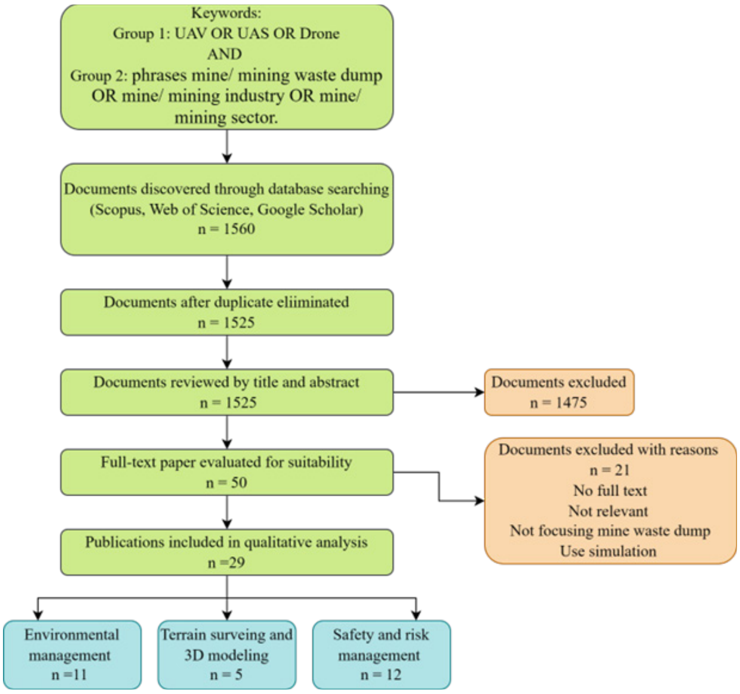


Fig. 1. Study selection process

agement of mine waste dumps. Therefore, this paper aims to perform a review on UAV applications in mine waste dumps to partially fill the aforementioned gap. The authors believe that the paper, one of the first in this field, can assist in advancement of UAV technology and develop them into a tool just as widespread in the field of mine waste dump managing and monitoring.

2. Methodology and Data

In this paper, a systematic literature search was carried out to assess scientific works involving UAV applications for mine waste dumps. The study selection process shows in Figure 1.

2.1 Eligibility criteria

The search results can be filtered based on language, year of publication, and subject field. Only reviews and papers in the English language were selected, and the search was restricted to materials published after 2010. Subjects unrelated to UAV application in mine waste dumps were not included in this study. In addition, duplicate papers or articles that concentrated on simulations rather than actual data were also excluded.

2.2 Information sources and search

For this review, relevant publications were identified on Web of Science, Google Scholar, and Scopus by searching the titles, abstracts, or keywords. The search has been carried out from January to May 2023.

The keywords were categorized into two main groups: the first group was involved with tools including the terms UAV, or UAS, or Drone, and the second group was associated with the interest field including phrases mine/ mining waste dump or mine/ mining industry or mine/ mining sector. At that time, the searchers used the "AND" Boolean operator to connect groups of keywords. The obtained results were exported to EndNote. The duplicates were eliminated using this software, and then appropriate research was extracted after a preliminary title and abstract screening. The information from each study was retrieved such as publication year, authors, nation, paper objective, type of UAV and camera, software technique, and critical findings. This data was then put into Microsoft Excel to analyze further.

3. Results and discussion

UAVs open up new possibilities for mining engineers, by providing aerial views that are challenging to obtain using traditional methods. Table 1 shows some applications of UAV technology in mine waste dumps. The obtained results indicated that most applications of UAV in mine waste dump focus on the areas of environmental management, terrain surveying and 3D modeling, and safety and risk management.

3.1 Environmental management

According to Wang et al. (2014), waste products from mining are produced in substantial quantities, and as lower-grade ores are used in mining, it is anticipated that the number of waste products will rise in the future [30]. Tailings are one of the waste types created, and they are made up of water, together with coagulants and flocculants as well as solid leftovers after mineral extraction [31]. One of the biggest environmental dangers in mining locations is tailings impoundments. There are many studies to identify the potential of using UAVs to monitor tailings impoundments. Because the use of UAVs as a quick and adaptable data collecting system to create orthomosaics and three-dimensional models has grown in popularity, this system can make it possible to monitor mine waste facilities economically and effectively [32]. In a study of [33], the authors revealed that UAV-assisted tailings impoundment monitoring is accurate enough to support management tasks including volume estimates and surface movement tracking down to the decimeter level. Also related to the tailings impoundments, [34] combined the use

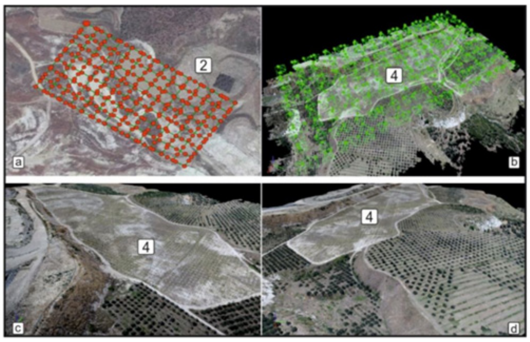


Fig. 2. UAV data on dump site. (a) UAV flight plan; (b) UAV position on Amygdolus Communis plant areas; (c) and (d) Solid models [39]

Fig. 3. Digitisation of the stockpile boundary on the point cloud dataset [48]

of UAV with traditional geochemical and photogrammetric methods to evaluate potential pollution through a categorization of tailings utilizing two hazard indexes, as well as calculate the volume of eroded material and past erosion rates of the abandoned mine tailings impoundments II and III in the town of Nacozari de Garca. According to [35], the tailings reservoir is a dispensable component of the operation of metal mines, and because it typically accumulates waste materials and wastewater, a source of artificial debris flows with high potential energy has been created, increasing the environmental risk. Therefore, they use UAV hyper-spectral imaging and ground-based hyper-spectral data to undertake an extensive aviation-ground disaster and environmental monitoring of the tailings reservoir.

Numerous minerals are exposed to oxidizing conditions throughout the mining process, especially sulfide minerals, which are then broken down by water to produce acidic mine water. Mining-related acid mine drainage (AMD) can contaminate local rivers and lakes and result in severe ecological issues [36]. Compared to traditional methods, UAV technology has benefits regard to security, image accuracy, and real-time imagery. Therefore, many scientists used this approach to study acid mine drainage. In order to identify this environmental phenomenon caused by mining, [36] used a UAV aerial photography system equipped with a Red, Green, Blue (RGB) camera to acquire extremely high-resolution photos of the stone coal mine in China. The images were then classified using support vector machine (SVM), random forest (RF), and U-Net methods, and the distribution of five different types of land cover, including AMD, vegetation, water, roof, and bare land, was identified. Similarly, [37] described the initial findings of an examination into acid mine drainage flows, nearby land, and sulfide-bearing mine tailings dumps in Russia using the integration of geophysical, geochemical data and UAV images. A photogrammetric method of aerial photography was used to record the morphology of the terrain and generate a digital elevation model at the study area.

The dump sites, which are created in the proximity of the mine regions, are frequently bigger than the sites when actual mining is taking place. Thus, rehabilitating waste dumps is a critical and mandatory action [38]. Various research demonstrated the effective usage of UAVs in the rehabilitation processes at the mine waste dumps. [39] produced vegetation index maps of a mining dump site that had been rehabilitated using UAV photogrammetry. These maps were utilized to assess the plant species' adaptation, health, and chance of survival. Figure 1 shows the flight plans for the flights, the position of the UAV on the site, and the solid model of the sites produced from the point cloud. The same goal as [39], [40] used high-resolution UAV visible and near-infrared (NIR) imagery to evaluate the success of vegetation establishment on the SP11 waste rock dump and the abandoned D2808 road stretch in Namibia. In addition, according to [41], monitoring the composition of vegetation species is critical for determining the efficiency of ecological restoration and managing biodiversity after restoration. Therefore, [42] used UAV LiDAR and hyperspectral images to study the structure and composition of the restored vegetation cover in semi-arid mine dumps. The vegetation intensity, height, and echo features were derived from LiDAR data, while the vegetation spectrum, index, and texture features were extracted from hyperspectral image data. In order to green the tailing dump, [43] recognized that the storage area on the investigated surface needs to be arranged, geometrized, weeded, and forested. In this study, a 3D model that is as accurate to reality as possible was produced using a combination of satellite and photogrammetric techniques, and it will be crucial in the process of reforestation of the tailings dump. According to [44], coal-waste dumps are an essential component of the ecology and form the scenery of coal basins. Therefore, they showed an assessment of environmental changes related to land use and alterations in vegetation on self-heating coal waste dumps

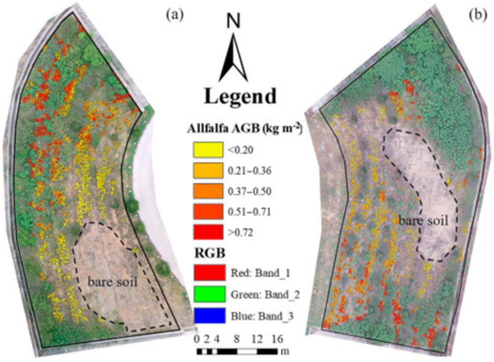


Fig. 4. Alfalfa aboveground biomass estimated results of the study area. (a) and (b) are Areas A and B, respectively. The black dotted polygon is the bare soil area with no vegetation coverage [61]

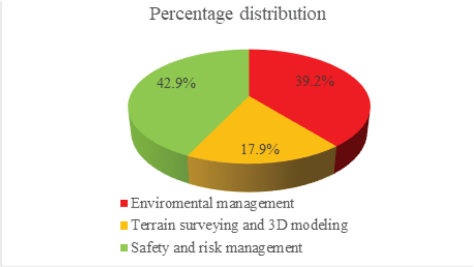


Fig. 5. Percentage distribution and number of publications of UAV applications in mine waste dumps

of various ages using UAV and infrared camera. The obtained findings revealed that when burning coal waste dumps. if the object is not sufficiently protected against the growth of fire, adding vegetation has no effect.

The use of hyperspectral imagery has also proven to be helpful for soil environmental monitoring of mine waste dumps. In the study of [45], the authors integrated UAV hyperspectral imagery with the simulated annealing deep neural network model to predict soil organic matter and available copper in the mine tailings pond of China. 74 samples of soil were taken from the study region, and their available copper (Acu) and soil organic matter (SOM) were calculated. Finally, maps of the distribution of ACu and SOM in the study area were established.

According to [46], the dumping sites, with a considerable volume of peeling material, are barren, with high slopes, untable slopes and soil compaction platforms, complicated material composition, and irregular subsidence. This causes a significant amount of vegetation communities to be destroyed and dramatically increases the possibility of soil erosion. Thus, to determine how much erosion occurs in gullies, [47] collected data using UAV oblique photography and created a thorough 3D model of the gully. The obtained results indicated that it might be simple to acquire the distinctive features of the typical erosion gullies of open-pit mine dumps using UAV-based 3D model and GIS spatial analysis technologies.

3.2 Terrain surveying and 3D modeling

According to [48], the ecology was significantly harmed by the abandonment of the waste in various dump sites during exploitation. Nevertheless, abandoned mounds are still rich in rare earth metals and possibly even valuable metals. These dump locations could create a brand-new potential stockpiles, which might pique the interest of business organizations. Therefore, it is necessary to locate dump sites and determine the bottom and top stockpile surfaces. In order to do this, the authors used UAVs to create a 3D topographic map and a 3D model of waste dumps in Mathiatis, Cyprus. The 3D model of reconstructed waste piles can be utilized to compute their volume and other factors such as the gradient of slopes, that are essential to help determine how much the cost of possible restoration. The boundary line of the stockpile was generated on the point cloud itself as Figure 2. Also for the purpose of generating 3D models, in the study of [49], a precise 3D model of waste dump was produced using a combination of satellite and photogrammetric techniques, and it will play a key role in the effort to green the waste dump of the Ucicani mine. The volumes of deposited waste ore could be calculated using the three-dimensional model, and an overview map of the waste dump area that will be greened up could be made.

The accurate mapping and 3D construction of a mine waste dump play an important role to monitor its stability. Acquisition and monitoring of elevation data is a critical issue in relation to some later reclamation activities in waste dumps, such as vegetation planting, soil covering, and cultivation mode. For change detection and analysis, it is crucial to produce digital surface models (DSMs) quickly [50]. Previous research showed that many parameters have an impact on the accuracy of UAV-based DSMs, including the number and distribution of ground control points (GCP) [51]. Thus, for the purpose of producing precise DSMs from UAS in a coal waste dump, they suggest an enhanced GCP configuration.

To broaden knowledge about the cascading behavior of the run-of-mine material during and after dumping, [52] used UAVs with mounted cameras to create photogrammetric models of dumps. Then, a technique for creating high-fidelity models (HFMs) of dump profiles was developed and studied in order to more thoroughly analyze this phenomenon. The

Tab. 1. Applications of UAV technology in mine waste dumps

Number	Resources	Year	Application	Objective
1	[33]	2017	Environmental management	Monitoring Tailings Inpoundments
2	[47]	2019		Analysis of the Development of an Erosion Gully
3	[34]	2019		assess potential pollution through a classification of tailings
4	[35]	2019		Study environmental monitoring of the tailings reservoir
5	[45]	2023		The prediction of organic matter and available copper n the mine tailings pond
6	[43]	2022		Study the process of afforestation of the tailings dump
7	[36]	2023		Recognize acid mine drainage
8	[37]	2022		The investigation of sulfide-bearing mine tailings dumps, as well as the surrounding terrain and acid mine drainage flows
9	[42]	2022		Study the Structure and Composition of the Restored Vegetation Cover in Semi-Arid Mine Dumps
10	[40]	2018		Assess the effectiveness of vegetation establishment on the waste rock dump
11	[44]	2020		Assessment of environmental changes related to land use and alterations in vegetation on self-heating coal waste dumps of various ages
12	[39]	2019		Study the rehabilitation processes at the mine waste dumps
13	[48]	2023	Terrain surveying and 3D modeling	Create a 3D model
14	[49]	2020		3D modelling of the tailings dump
15	[30]	2020		Modelling a hypothetical tailings dam
16	[51]	2020		Generate accurate DSMs
17	[52]	2022		Generate photogrammetric models of dumps
18	[54]	2020	Safety and risk management	Monitoring of deformations at the adjacent dump site
19	[17]	2022		Analyze the stability of active mine waste dump slope
20	[56]	2023		Determine particle size distribution
21	[55]	2022		Analyze particle size distribution
22	[26]	2022		Warn spontaneous combustion of coal waste dump after reclamation
23	[63]	2020		Assess the deformation activity of open-pit mine dump site
24	[58]	2016		Classify the index for self-heating intensity
25	[60]	2021		Determine influence of water erosion on fire hazards
26	[57]	2017		Determine particle size distribution
27	[59]	2022		Investigate the influence of water erosion on fire hazards
28	[61]	2022		Detect the spontaneous combustion monitoring of coal waste dumps
29	[62]	2022		Investigate the land degradation and soil erosion at an opencast coal mine dump

findings indicated that the HFMs developed in this study may be used to calibrate computer models of dumps so that they more closely resemble reality.

In contrast to water-retaining dams, which are typically constructed using concrete, rock, or soil, tailings dams are typically constructed utilizing the tailings themselves to reduce expenses [53]. As a result, operations and emergency management are frequently more difficult due to increased risks of disasters involving dam breaches, debris flows, or overtopping [30]. A model of the run-out flow of tailings dam breach was proposed by using UAVs SfM-photogrammetry and field surveys in China. The findings showed that UAV imagery can generate accurate enough data to assist tailings management activities and monitor yearly surface displacements in the decimeter range [30].

3.3 Safety and risk management

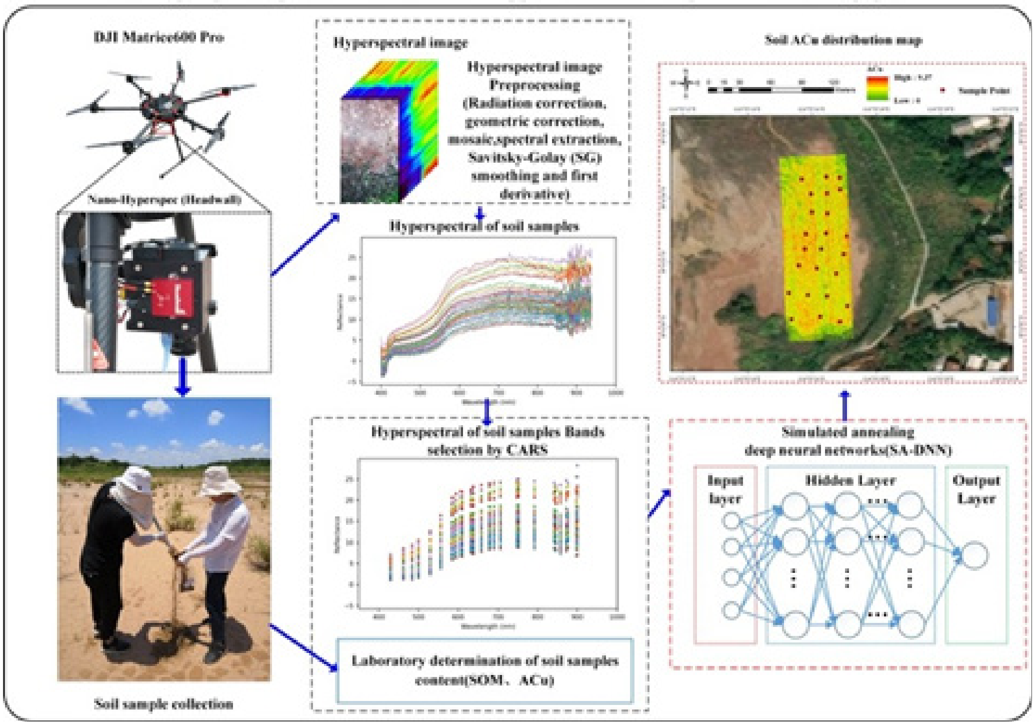
For both security and the continuation of mine production, it is crucial to identify and monitor potential deformations in the benches of dump sites of open-pit mines. [54] used the Global Navigation Satellite System (GNSS) method assisted with UAV technology to monitor and determine the deformation of dump sites of three different open-pit marble mines in Turkey. In this study, the GNSS approach identified the locations of displacements, and UAV photogrammetry investigated the reasons for mobility at the location as well as its areal and volumetric sizes. The obtained results revealed that monitoring of deformations using the combined utilization of UAV photogrammetry and the GNSS approach will enable the effective identification of the primary variables that may contribute, particularly to slope failures, and taking the timely implementation of necessary preventive measures.

During the open-pit mining process, the excavated soil received no economic benefit to the mining sector. These items are categorized as waste which is dumped forming a slope. Mine waste dumps are created quite quickly, therefore these dump slopes are really large. This hurried approach is increasing the risk of disasters on the slopes of dumps. Thus, it is necessary to analyze the stability of mine dump slope and this is a primary subject in geotechnical engineering. [17] analyzed the stability of an operational in-pit mine waste dump using UAV imagery, DGPS survey, and geotechnical samples gathered from the study area. With the aid of UAV photos, 3D modeling, and accurate geometry are retrieved from the active waste dump slope. The findings proved that the UAV's accessibility and image sensor advancements are helpful for building 3D maps and models of the mining regions.

The particle size distribution (PSD) is necessary for assessing the mechanical characteristics of the materials (rock fill) deposited at mine waste dumps, particularly their shear strength. [55] studied the use of UAV photogrammetry to characterize the shear strength in waste dump materials and the impact of PSD on shear strength. The UAV-based map can show the geometric characteristics of the rock fill and waste dump particles. Also to determine PSD, the workflow and the results for PSD evaluation of waste rockfill materials using UAV images were presented in the study of [56]. In addition, PSD is also one key element that governs the flow behavior in ore/rock beds. Because traditional sieve analysis has its limits, [57] used UAV imagery to examine the PSD in ore piles. Analyzing images captured by the camera mounted on a UAV allowed researchers to characterize the PSD of the dump leach pad at the case study mine.

According to [58], after depositing, the mining waste material starts to weather as a result of organic matter oxidation and other processes, which could subsequently result in self-heating. Emissions from dumps have a negative impact on both human and animal life. Due to its negative impact on

Fig. Make a soil available copper distribution map in the mine tailings pond by using that the combination the SA-DNN model and UAV hyperspectral imagery [45]



the environment and human health, it is essential to identify the self-heating process as soon as possible in order to avoid the spread of impacted areas and put out self-combustion zones. In order to do this, in study [58], the authors use Landsat, ASTER, and thermal-infrared camera collection from a drone to generate a classification index for self-heating intensity at coal waste dumps in various areas combining Landsat 4-5 TM, ETM+, and ASTER photographs.

Up utill now, the influence of intense rainfall and water erosion on spontaneously combusting of coal waste dumps has gained no much attention. As a result, the concern arises as to whether heavy rain can cause water erosion of the dump slope, increasing the likelihood of the dump's self-ignition. For this purpose, [59] studied the amount of rainfall, changes in the status of the slope surface, and the thermal operation of the chosen dump. Moreover, the state of mining waste dumps is impacted by precipitation, especially intense rainfall. The influence of rainfall on the erosion of water on a coal waste dump's slopes and its thermal condition presented in the study of [60]. The study's objective was to depict the beginning conditions of the studied dumping ground surfaces and the thermal conditions of particular slopes. With the assist of UAV-based low-altitude aerial photogrammetry, terrestrial laser scanning, observations of temperature and gas concentrations, the occurrence of phenomena like water erosion and thermal activity at the coal waste dump has been determined. As can be seen, spontaneous burning of coal waste dumps is one of the major issues in mining regions. Even after ecological restoration and land reclamation, this danger still occurs. [61] proposed better technology, UAV RGB imagery based on alfalfa aboveground biomass, for monitoring coal waste dumps for spontaneous combustion, which might serve as a guide for early detection and prevention in mining areas. Stepwise linear regression models were used to estimate this plant aboveground biomass together with the vegetation index and texture metrics taken from UAV RGB data. The alfalfa aboveground biomass map of the research area was created based on the model as Figure 3.

A rehabilitated opencast coal mine waste is influenced by erosion caused by wind and water from natural processes after artificial management is discontinued, leading to land deterioration as well as safety incidents. In order to degree and spatial distribution of erosion cracks and the soil erosion and land degradation after 5 years of natural processes, a multi-source data collection approach was used [62]. In this study, a UAV was used to gather the position and intensity of soil erosion as well as high-precision topography parameters and by using field sampling, the topsoil's physical characteristics were discovered. Moreover, [63] insisted that UAV can be a helpful instrument to monitor long-term continuous deformation and soil erosion. Therfore, UAV images were utilized to aid in phase unwrapping, demonstrating the soil erosion and deformation of the open-pit coal mine dump in China. In this study, high-resolution UAV images play an important role to understand the developmet of the waste dump. The elimination of the topographic factor and a time series analyses were processed using the high-resolution DEM (8 cm/pix) generated by UAV, structure from motion, and multi view stereo technologies.

3.4 Discussion and recommendation

From the review, it was determined that several trends helped to categorise current UAV uses in the mine waste dumps, as follow:

(1) Environmental management (eleven papers)
(2) Terrain surveying and 3D modeling (five papers)
(3) Safety and risk management (twelve papers)

Figure 4 displays the percentage distribution of each UAV application related in mine waste dumps together with number of publications categorized under that application. The obtained results show that there are very few studies on the application of UAVs in mine waste dumps, so this is a new approach that has not received much attention. Published papers focus more on environmental management and safety and risk management. There are only 5 studies with the aim of terrain surveying and 3D modeling, mainly papers used UAV to generate DEM, DSM, 3D models for purposes related to the landscaping, geometry, weeding and afforestation in mine waste dump [49], tailings dam [30], waste material stock-piles [48], mine haul truck dumping process [52]. In addition, publications involved environmental management primarily concentrate on environmental monitoring of the tailings reservoir [33-35, 43, 45], identifying acid mine drainage [36, 37], assessing environment of waste dumps [40, 42, 44]. For safety and risk management in mine waste dumps, UAV application focus mostly on deformation monitoring [54, 63], stability analysis [17], determination of particle size distribution [55-57], detection of spontaneous combustion [26, 58, 61], investigation of soil erosion [59, 60, 62].

Furthermore, the results of the review showed that most of the studies were conducted in recent years and the number increased gradually over the years, from 1 study in 2016 to 10 studies in 2022. Despite the fact that an increase in studies on the use of UAVs to address mine waste dump management indicates a growing trend in the scientific literature, there is a certain delay among researchers in assessing the extensive usage of UAVs in the field of mine waste dump management. Accordingly, the understanding of the potential of UAV for addressing issues with mining waste dumps remain inadequate and needs to be developed. Most studies used digital images, except for spontaneous combustion studies using infrared camera. The SfM technique improves image post-processing and enables the quick creation of any necessary models. Two software programmes that use SfM algorithms to create extremely accurate photogrammetric models were frequently mentioned in the literature including Agisoft Photoscan and Pix4D.

According to [64], UAVs' quick mobility makes multi-view geographical data collection easier. Besides, compared to other remote sensing platforms, a UAV can get closer to a target object. As a result, it is easy to acquire high-resolution images. This closes the gap between present aerial and ground platforms, opening up new possibilities for building high-fidelity 3D models. Furthremore, due to its small form and remote operating abilities, a UAV can gather spatial measurements in an adverse condition that is too risky or inaccessible for other traditional mapping technologies, especially in hazardous or heavy metal contaminated areas such as mining waste dumps. However, managing the enormous number of datasets being collected is a problem that UAV applications frequently face. Thus, the superiority in time efficiency that is an advantage of UAV technology is reduced by the delayed processing of datasets captured by UAVs. In order to overcome this shortcoming, according to [64], it is ideal for all processing steps to be totally automated, requiring no human involvement. Recent developments in artificial intelligence and computer vision technologies may be able to support and give an efficient solution for UAV usage in mining waste dump management. In fact, this technology was used in study of [45] that the combination the simulated annealing deep neural network (SA-DNN) and UAV hyperspectral imagery to make a soil available copper distribution map in the mine tailings pond. The process of using this advanced technology for mapping soil available copper content in the mine tailing pond is shown in Figure 5.

4. Conclusion

Although the fact that the scientific community first learned about UAV use in the mining industry more than a decade ago, only in the past six to seven years have there been intensive investigations of the potential of UAV in managing mine waste dump. Based on the analysis of the available literatures as well as findings of current study, it was found that UAV technology has a lot of potential for managing mine waste dumps. Additionally, a list of potential uses for UAVs in mine waste dumps was provided including environmental management, terrain surveying and 3D modeling, and safety and risk management. Many obstacles still exist, though, and they need to be further investigated. In the near future, we may anticipate a continuous rise in research publications related to the usage of UAVs in mine waste dumps.

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