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Assessment of the impacts of synclinal structures on safety and efficiency in underground coal mining: A case study in the Quang Ninh coal basin

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Abstract: Synclinal bottoms represent structurally complex zones that contain significant coal resources but also pose major technical and safety challenges for underground coal mining. In the Quang Ninh coal basin (Vietnam), many underground mines are currently approaching synclinal bottoms under conditions of increasing mining depth, complex geology, and limited mechanization. However, systematic assessments of the impacts of syncline geometry on mining organization and technical solutions remain limited. This study investigates the characteristics and mining implications of synclinal bottoms in typical underground coal mines in the Quang Ninh region, with a focus on seam geometry, hydrogeological conditions, gas accumulation, and ground stability. A combined methodology integrating geological analysis, field investigation, and comparative assessment was applied to classify synclinal bottoms into bowl-shaped and trough-shaped types. Their influences on mine opening systems, panel layout, ventilation, drainage, and mining efficiency were evaluated. The results indicate that synclinal bottoms significantly differ from seam limbs in terms of seam dip variability, water and gas concentration, and strata behavior, leading to increased difficulties in longwall arrangement, drainage, and ventilation. Mining performance is strongly controlled by syncline geometry and opening schemes. Synclines developed from the bottom upward with gravity drainage show better safety and recovery efficiency, whereas closed or deeply seated synclinal bottoms are associated with higher coal losses and operational risks. The study emphasizes that synclinal bottoms should be treated as specialized mining units rather than extensions of seam limbs. The findings provide a scientific basis for selecting appropriate mining solutions for different syncline types and contribute to safer and more efficient underground coal mining in the Quang Ninh coal basin and other structurally complex coalfields.
Keywords: Synclinal bottom, mine ventilation, mine drainage, underground coal mining, water accumulation

1. Introduction

Underground coal mining in structurally complex coalfields is increasingly challenged by geological conditions that strongly affect mine safety, productivity, and resource recovery[1]. Among these conditions, synclinal structures play a dual role: they often contain substantial coal reserves but simultaneously create unfavorable mining environments due to complex seam geometry, water accumulation, gas concentration, and intensified strata stress[2]. As mining activities advance to greater depths, synclinal bottoms are becoming critical targets that require specialized technical solutions rather than conventional mining approaches applied to seam limbs.

In many coal basins worldwide, synclinal areas have been identified as high-risk zones in underground mining[3]. Studies in China have shown that closed or deeply seated synclinal bottoms are prone to water inrush, gas accumulation, and abnormal strata behavior, necessitating multi-level opening systems and pre-drainage measures before extraction[4]. Similar challenges have been reported in coalfields in Poland and Germany, where synclinal structures significantly influence longwall layout, ventilation networks, and ground control strategies[5, 6]. In Australia, large-scale mechanized longwall operations have demonstrated that mining efficiency in synclinal zones strongly depends on syncline geometry, drainage capability, and the integration of geological analysis into mine planning[7].

In Vietnam, underground coal mining is concentrated mainly in the Quang Ninh coal basin, which is characterized by complex folding and faulting. Synclines are widely distributed in most underground mines, such as Nam Mau, Vang Danh, Ha Lam, Duong Huy, Khe Cham, and Mao Khe[8]. These synclines vary in scale and morphology and are frequently intersected by faults, resulting in highly heterogeneous geological conditions. Synclinal bottoms in this region are typically associated with concentrated mine water, methane accumulation, and increased deformation of roadways and longwall faces. Despite their importance, synclinal bottoms in Quang Ninh have often been treated as extensions of seam limbs, with limited differentiation in mine opening design, panel layout, and mining technology[9].

Previous studies in Vietnam have mainly focused on individual technical aspects of synclinal mining, such as drainage methods, ventilation safety, or ground control in specific mines[10]. However, a comprehensive framework linking syncline geometry with mining organization and the selection of appropriate mining solutions remains insufficient. In particular, the influence of different synclinal bottom types such as bowl-shaped and trough-shaped synclines on mine opening systems, panel division, and operational risks has not been systematically evaluated[11].

Therefore, this study aims to provide an integrated assessment of synclinal bottoms in underground coal mines in the Quang Ninh coal basin. The objectives of the study are: (i) to classify synclinal bottoms based on their geometric characteristics; (ii) to analyze their impacts on mine opening schemes, panel layout, ventilation, drainage, and mining efficiency; and (iii) to identify critical constraints and propose suitable mining solutions for different syncline types. By treating synclinal bottoms as specialized mining units, this study seeks to contribute to safer and more efficient underground coal mining in Quang Ninh and other structurally complex coalfields worldwide.

2. Study area

The study focuses on two areas exhibiting the most representative synclinal geological characteristics in the Quang Ninh coal basin. The first is the Nam Mẫu coal mine, located in the Uông Bí area, where preparation and extraction activities are being conducted at the synclinal bottoms of seams 9, 8, 7, and 6A, which display different geometric scales and morphologies. Among these, the synclines in seams 8 and 9 are large in scale and are designed to be mined as independent blocks. Seam 7 at the −50 m level represents a key area where a two-level access scheme is applied, utilizing cross-measure roadways and rock raises to approach the synclinal bottom, thereby optimizing the control of mine water and gas. In parallel, the Nam Khe Tam coal mine, operated by Company 86 in the Cẩm Phả area, exploits seams 18, 12, 11, and 9, which are characterized by elongated trough-shaped synclines. In this mine, synclinal bottoms are commonly divided into two limbs and extracted simultaneously together with coal seams at higher levels. The mine provides extensive practical experience in managing combined forced and gravity drainage under conditions of strongly variable seam gradients. Together, these two study areas form an important dataset representative of the two most common synclinal morphologies—elongated trough-shaped and bowl-shaped synclines—allowing a reliable assessment of ventilation and drainage risks under current underground mining conditions. These geological settings result in low and irregular roadway gradients, long ventilation routes, and natural water accumulation zones, making ventilation control and drainage at synclinal bottoms particularly challenging

3. Methodology

This study employs an integrated methodological framework to evaluate ventilation and drainage conditions at synclinal bottoms in underground coal mines and to identify the key constraints imposed by syncline geometry on mining organization. The methodology combines geological analysis, field investigation, and comparative assessment to ensure a systematic and solution-oriented evaluation.

3.1. Data collection and geological analysis

Geological and mining data were collected from representative underground coal mines in the Quang Ninh coal basin, including Nam Mẫu and Nam Khe Tam mines. The dataset comprises geological maps, seam cross-sections, mine layouts, opening schemes, and technical reports related to mining activities in synclinal areas. Special attention was paid to seam geometry, syncline morphology, fault distribution, and bottom elevation, as these factors directly control groundwater convergence, gas accumulation, and strata behavior. Based on horizontal seam projections and the intersection of coal seams with horizontal planes, synclinal bottoms were classified into two main types:

- Bowl-shaped synclines, characterized by near-circular intersections;
- Trough-shaped synclines, characterized by elliptical intersections.

This classification provides the geometric basis for subsequent comparative analysis.

The main synclinal bottoms currently encountered in representative underground coal mines of the Quang Ninh coal basin, together with their geometric characteristics, opening schemes, and dominant ventilation and drainage features, are summarized in Table I[11].

3.2. Field investigation and operational assessment

Field investigations were conducted at selected underground coal mines to observe actual ventilation and drainage conditions at synclinal bottoms during roadway development and longwall extraction. Observations focused on airflow distribution, methane occurrence, water inflow, roadway stability, and the performance of ventilation and drainage systems. Information on ventilation methods, fan configurations, drainage layouts, pumping systems, and safety management practices was collected and synthesized. Key operational indicators, including ventilation complexity, drainage effectiveness, coal recovery, and operational reliability, were used to assess mining performance at synclinal bottoms and to compare these conditions with those observed at seam flanks.

Field observations were conducted across different mining stages to capture both development and production conditions. Emphasis was placed on identifying recurring technical difficulties rather than isolated incidents, ensuring that the assessment reflects representative operational patterns at synclinal bottoms.

Table I: Main synclinal bottoms in underground coal mines of the Quang Ninh coal basin

Mine	Syncline name	Bottom elevation (m)	Syncline type	Relative scale	Main opening scheme	Drainage characteristic	Ventilation characteristic	Mining status
Nam Mau	H6	−60	Bowl-shaped	Large	Two-level (cross-measure + raises)	Gravity-dominated with local pumping	Complex, multi-control structures	Active
Nam Mau	H7	−50	Trough-shaped	Large	Two-level	Gravity-dominated	Moderate complexity	Active
Nam Mau	H8	+20	Trough-shaped	Medium	Inclined rock roadway + raises	Gravity-dominated	Moderate complexity	Active
Nam Mau	H9	+50	Bowl-shaped	Medium	Inclined coal roadway	Gravity + forced pumping	Complex	Active
Nam Khe Tam	…	…	Trough-shaped	Medium	Two-level	Gravity-dominated	Moderate	Active

3.3. Conceptual analysis and integration

To clarify the causal relationships between syncline geometry and mining constraints, a conceptual block diagram was developed (Fig. 1), illustrating how synclinal bottom geometry controls ventilation resistance, gas accumulation, water convergence, and associated technical challenges. In addition, a simplified conceptual framework (Fig. 2) was constructed to illustrate the organization of ventilation and drainage systems at synclinal bottoms, highlighting their interactions with panel layout, roadway geometry, and mining sequence. By integrating geological classification, field observations, and conceptual modeling, the methodology establishes a coherent basis for evaluating ventilation and drainage risks and for supporting solution-oriented discussion.

4. Results and Discussion

4.1. Current Status and Assessment of Ventilation at the Synclinal Bottom

4.1.1. Current Ventilation Practices

Ventilation of development roadways

At synclinal bottoms, forcing ventilation is widely applied during roadway development. Fresh air is supplied to the working face through rubber-coated fabric ducts, with the duct outlet distance adjusted according to the advance rate and current safety regulations. For long development roadways, several mines have transitioned from serially connected small-capacity fans to multi-stage auxiliary fan systems (e.g., FBD and VME), significantly improving airflow stability and reducing pressure losses. Methane (CH_4) concentrations are generally well controlled through a combination of handheld gas detectors and automatic gas monitoring and alarm systems. However, the curved geometry of roadways along synclinal axes increases aerodynamic resistance, particularly at bends and intersections, which complicates airflow distribution, as conceptually illustrated in Fig. 1.

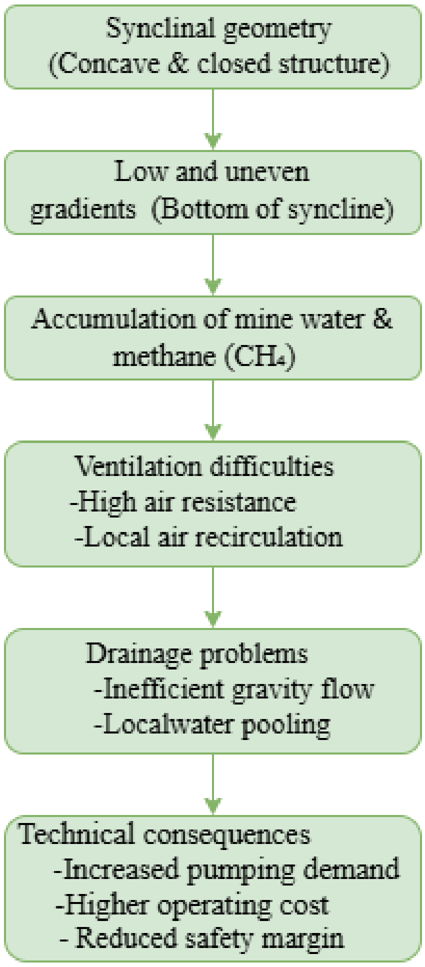

Figure 1. Conceptual block diagram illustrating the chain of impacts of synclinal bottom geometry on ventilation and drainage conditions in underground coal mining.

Ventilation of longwall faces

Ventilation at longwall faces located in synclinal bottoms is mainly provided through the mine-wide ventilation system. Although airflow direction, velocity, and quantity generally meet design requirements, the undulating geometry of seams and roadways results in locally increased resistance. Consequently, numerous ventilation structures such as air doors, regulators, ventilation bridges, and auxiliary fans are required to separate intake and return airways and to maintain stable airflow conditions (Fig.2).

These ventilation characteristics highlight the strong influence of synclinal geometry on airflow resistance and ventilation organization

4.1.2. Assessment of Ventilation Performance

Overall, the applied ventilation measures effectively ensure safety during both roadway development and longwall extraction at synclinal bottoms. Harmful gas concentrations remain within permissible limits, and underground microclimatic conditions generally comply with regulatory requirements. Nevertheless, compared with seam flanks, ventilation at synclinal bottoms is more complex and costly. The extensive use of ventilation control structures increases air leakage and operational difficulty, while the maintenance of long return airways imposes additional burdens. A synthesis of ventilation practices, advantages, and limitations at synclinal bottoms is presented in Table II. In practice, ventilation-related operating costs at synclinal bottoms are consistently reported to be higher than those at seam flanks due to increased resistance and system complexity.

4.2. Current Status and Assessment of Drainage at the Synclinal Bottom

In addition to ventilation challenges, drainage represents another critical constraint directly controlled by synclinal bottom geometry.

4.2.1. Current Drainage Practices

Drainage during roadway development

Drainage during roadway development at synclinal bottoms is mainly gravity-driven, using side ditches along roadways. Typical ditch cross-sectional areas range from 0.15 to 0.30 m², which is generally sufficient to convey inflow water during excavation. Sedimentation sumps are installed at intervals of 150–200 m to reduce silt accumulation. However, due to the very low and uneven gradients typical of synclinal bottoms, gravity drainage efficiency is often limited. Rapid sediment deposition in ditches increases maintenance requirements and reduces long-term drainage performance.

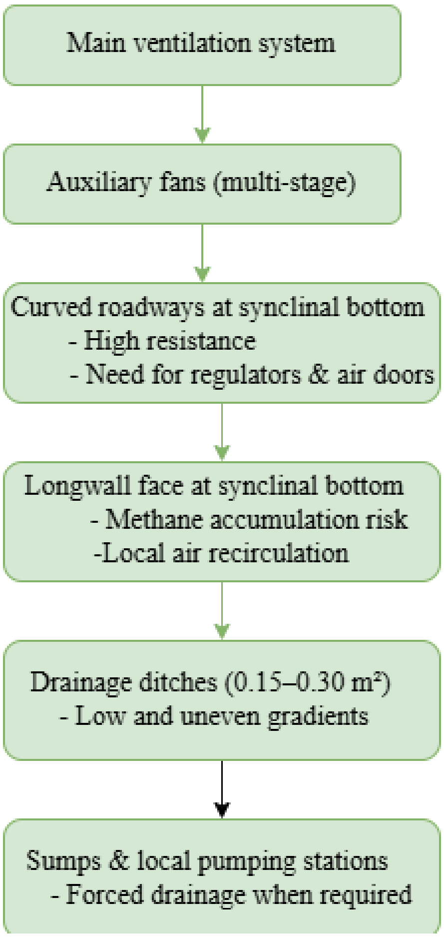

Figure 2. Conceptual framework showing the organization of ventilation and drainage systems at synclinal bottoms in underground coal mines.

Table II: Summary of ventilation practices and associated challenges at synclinal bottoms.

Aspect	Current practice	Main advantages	Key limitations
Ventilation method	Forced ventilation (ducted)	Flexible, easy to deploy	High leakage, pressure loss
Fans	Multi-stage auxiliary fans (FBD, VME)	Suitable for long roadways	Increased power consumption
Airflow control	Air doors, regulators, overcasts	Effective airflow separation	Complex adjustment
Methane control	Handheld detectors & automatic sensors	High safety level	Local accumulation risk
Overall assessment	Technically feasible	Ensures compliance	High operating cost

Drainage at longwall faces.

At longwall faces, drainage primarily relies on gravity flow toward lower-level gate roads. In some mines, gate roadways are intentionally arranged beneath synclinal bottoms to enhance water collection. In bowl-shaped synclines or where gate roads are constructed at the same elevation as the synclinal floor such as in Nam

Mau mine local water accumulation frequently occurs. In these cases, temporary sumps and underground pumping systems are required to transfer water to central reservoirs through the mine drainage network. The absence of systematic pre-drainage measures results in persistent water accumulation in faces and low-gradient roadways, adversely affecting mining operations.

4.2.2. Assessment of Drainage Performance

Field investigations at Nam Mau and Nam Khe Tam mines indicate that drainage at synclinal bottoms currently relies on a combination of gravity drainage and forced pumping. While gravity drainage remains the dominant mode, its effectiveness is constrained by synclinal geometry, which promotes water pooling and sedimentation. Forced pumping is essential in bowl-shaped synclines and locally depressed areas, effectively mitigating immediate safety risks but significantly increasing operating costs and system vulnerability under harsh underground conditions. Drainage characteristics, limitations, and technical implications at synclinal bottoms are summarized in Table III.

Table III: Characteristics and limitations of drainage systems at synclinal bottoms in underground coal mines.

Drainage aspect	**Current condition**	**Technical implication**
Drainage mode	Gravity-dominated	Limited efficiency
Ditch cross-section	0.15–0.30 m^2	Frequent siltation
Gradient	Low and uneven	Water pooling
Pumping	Local forced pumping	Increased energy cost
Pre-drainage	Rarely applied	Higher water inflow risk

4.3. Discussion

The results demonstrate that synclinal bottom geometry exerts a fundamental control on both ventilation and drainage performance. Compared with seam flanks, synclinal bottoms exhibit higher ventilation resistance, greater methane accumulation potential, and stronger groundwater convergence, resulting in increased technical complexity and operational costs. The two-level access scheme applied at mines such as Nam Mau and Nam Khe Tam is generally appropriate, as it facilitates gravity drainage toward lower levels and reduces dependence on forced pumping. However, vertical offsets of synclinal axes between different seams frequently lead to localized water accumulation and increased ventilation resistance. These findings indicate that synclinal bottoms should be treated as a distinct mining unit rather than applying conventional seam-flank designs. The integrated influence of syncline geometry on ventilation and drainage organization is summarized conceptually in Fig. 1 and Fig. 2, providing a scientific basis for selecting targeted technical solutions adapted to different synclinal types.Table IV provides a comparative assessment of ventilation and drainage conditions between synclinal bottoms and seam flanks, emphasizing how syncline geometry leads to increased water accumulation, gas concentration, and higher technical demands in underground coal mining.

Table IV: Comparison of ventilation and drainage conditions between synclinal bottoms and seam flanks.

Criterion	**Synclinal bottom**	**Seam flanks**
Seam geometry	Concave, closed	Relatively stable
Water condition	Concentrated	Favorable drainage
Gas condition	Methane-prone	Better dispersion
Ventilation demand	High	Moderate
Drainage demand	High	Low
Mining risk	High	Low

5. Conclusion

This study provides an integrated assessment of ventilation and drainage conditions during coal extraction at synclinal bottoms in underground coal mines of the Quang Ninh coal basin. By combining geological analysis, field investigation, and conceptual modeling, synclinal bottoms were classified into bowl-shaped and trough-shaped types, and their distinct influences on mining organization were systematically evaluated. The results demonstrate that synclinal bottoms differ fundamentally from seam flanks in terms of seam geometry, groundwater convergence, gas accumulation, and ventilation resistance. These characteristics lead to increased technical complexity, higher operational costs, and elevated safety risks, particularly in closed or deeply seated synclinal bottoms. Ventilation at synclinal bottoms requires more complex airflow control systems and auxiliary ventilation measures, while drainage performance is strongly constrained by low and uneven gradients, often necessitating forced pumping in bowl-shaped synclines. The analysis confirms that appropriate mine opening schemes, especially two-level access systems that promote gravity drainage, can significantly improve safety and operational efficiency in synclinal zones. However, vertical offsets of synclinal axes between seams remain a critical challenge, frequently causing localized water accumulation and increased ventilation resistance. Overall, the study highlights that synclinal bottoms should be treated as specialized mining units rather than simple extensions of seam flanks. The conceptual frameworks and comparative assessments presented provide a scientific basis for selecting targeted ventilation and drainage solutions adapted to different synclinal types. The findings contribute to safer and more efficient underground coal mining in the Quang Ninh coal basin and offer valuable references for other structurally complex coalfields worldwide.

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