Journal of Mining and Earth Sciences

Website: https://jmes.humg.edu.vn

Geological characterization and mining potential of syncline-shaped seam in the Quang Ninh coal basin: from geological analysis and practical mining solutions

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ARTICLE INFO

Article history:
Received 05th Jan. 2026
Revised 11th Apr. 2026
Accepted 24th Apr. 2026

Keywords:
Mining layout optimization,
Quang Ninh coal basin,
Synclinal bottom geometry,
Underground coal mining.

ABSTRACT

The bottom areas of synclinal-shaped seams represent coal-bearing zones with significant resource potential. Under complex geological and hydrogeological conditions, they represent significanttechnical challenges for underground coal mining. This study investigates the impacts of synclinal bottom geometry on mining organization in underground coal mines in the Quang Ninh coal basin, Vietnam. An integrated methodology combining geological analysis, field investigation, and comparative assessment was employed to link synclinal-shaped seam geometry with mining layout, extraction systems, ventilation, and drainage conditions. Compared with seam limbs, the bottom areas of synclinal-shaped seams constrain mining organization and limit the applicability of high-level mechanization due to their unfavorable seam geometry, strong dip-angle variability, concentrated mine water, gas accumulation, and reduced strata stability. According to our comparative analysis, syncline-shaped seam accessed from the bottom and equipped with gravity-driven drainage systems generally achieve higher mining efficiency and lower hydro-gas risks. For closed bowl-shaped syncline seam, they tend to suffer from severe drainage difficulties and increased coal losses. A classification framework to guide the selection of appropriate development schemes and mining solutions for different syncline-shaped seam types is recommended using syncline-shaped seam morphology and scale. The findings highlight the necessity of treating the bottom areas of synclinal-shaped seams as special mining units and provide a scientific basis for optimizing underground coal mining in geologically complex and deepening mining conditions.

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DOI: 10.46326/JMES.2026.67(4).02

1. Introduction

Folds are fundamental tectonic structures generated under compressional tectonic mechanisms and are widely found in sedimentary basins worldwide (Morley et al., 2011). Their formation reflects the complex interaction between regional stress fields, lithological contrasts, and deformation history. Folds, therefore, can be considered as key indicators of basin evolution and structural framework. In coal-bearing basins, folds have a direct impact on underground mining conditions (Cheng et al., 2021) as coal seam geometry, thickness variation, continuity, and reserve distribution are under the control of the folding process. Variations in fold geometry affect critical factors of mine safety and productivity, including roof and rib stability, stress redistribution around excavations, the effectiveness of ventilation networks, mine drainage efficiency, and the accumulation and migration of methane and other hazardous gases (Nematollahi Sarvestani, 2021). The occurrence and migration of methane in coal seams are strongly influenced by geological structure and microstructural properties, which play a critical role in gas drainage and mine safety (Mishra et al., 2023). In structurally complex zones such as synclines, tectonic conditions significantly control coalbed methane enrichment and distribution patterns (Ye et al., 2023).

From a morphological and structural perspective, folds are commonly classified into major types which are anticlines and syncline-shaped seam. Other parameters including axial plane orientation, interlimb angle, symmetry or asymmetry, wavelength and amplitude, as well as scale (linear versus equidimensional folds) and genetic relationships with associated fault systems, can be used to categorize folds (Thang, 2016). All these attributes determine the three-dimensional configuration of coal seams and surrounding strata. Among these fold types, syncline-shaped seams (concave folds) are often associated with thicker coal accumulations due to depositional and post-depositional controls. However, they also present substantial challenges for underground mining. Synclinal troughs tend to act as natural collectors of groundwater and mine gas. This type of fold usually has a complex geometry, which produces both technical difficulty and operational risk for the establishment of access development, panel layout, and transportation systems (Colas et al., 2025). This characteristic has been confirmed in recent studies, where synclinal structures under confined aquifers exhibit significant roof water inflow risks and require specialized control measures (Luo et al., 2025).

Many extensive studies have investigated the interactions between geological structures and mining performance using advanced approaches, including intensive underground mining technologies and system optimization under complex conditions (Kazanin et al., 2021; Zhao et al., 2021). Also, hydrogeological analysis and advanced drainage or pre-dewatering strategies to manage water inflow in structurally complex zones were considered. Others concentrated on stress analysis and technical-economic analysis to evaluate strata stability and failure mechanisms around synclinal axes (Eremenko et al., 2020).To control the folds in mining activities, remote sensing and GIS-based techniques for monitoring surface and subsurface deformation have been proposed recently (Thao et al., 2025). In general, these studies have provided valuable results in the applications of adaptive mine planning, hazard prediction, and risk mitigation to improve safety and resource recovery in coal basins that are under the impact of folds (Fattahi et al., 2024)

In Vietnam, geological investigations of the Quang Ninh coal basin have established a solid foundation for detailed descriptions of fold distribution, structural evolution, and coal resource potential. While previous geological investigations in the Quang Ninh coal basin have provided detailed descriptions of structural evolution and reserve estimation (Hung & Dong, 2021), they often lack a systematic linkage to practical mining challenges. This study distinguishes itself by proposing a novel fold classification framework specifically designed for optimizing technical solutions in synclinal zones. Unlike conventional geological classifications, our framework integrates geometric parameters (morphology and scale) with operational mining metrics, such as drainage feasibility and mechanization potential. This approach allows for a proactive selection of mine development schemes, filling a critical gap in the transition to deeper and more complex mining conditions in Vietnam. In this context, the relationship between geological conditions and production sustainability in

Vietnamese coal mines has been emphasized, highlighting the need for specialized technical adaptations (Que et al., 2021).

Several key research gaps can be identified: (i) the absence of systematic comparative assessments between different syncline-shaped seam types based on operational mining metrics; (ii) insufficient integration of structural geological characterization with mine performance indicators, including recovery factor, coal losses, water inflow, gas emission, and ventilation difficulty; and (iii) the limited application of modern predictive and mitigation tools, such as coupled 3D structural andhydrogeological modeling, advanced dewatering technologies, and real-time monitoring systems, specifically adapted to the geological, technical, and economic conditions of underground coal mines in Vietnam. These shortcomings constrain the effectiveness of mine design and planning and reduce opportunities to optimize both safety and resource recovery in synclinal mining areas.

The goals of this paper are to: (1) link and identify the different types of folds that are typical in the Quang Ninh coal basin; (2) investigate the geological and technical conditions of representative synclinal structures; (3)show how structural features affect underground mining operations , such as access development, panel layout, haulage systems, ventilation, and drainage; and (4) propose practical research directions and technological solutions that are specific to the local geology and economy, establishing a scientific basis for better mine design and safer, more efficient coal resource exploitation in synclinal zones.

2. Study area

The Northeast Coal Basin covers an area of approximately 1,400 km^2, extending from Pha Lai (Hai Duong Province) to Cai Bau (Quang Ninh Province), and is subdivided into three main regions: Cam Pha, Hon Gai, and Uong Bi. The basin has a width ranging from 10 to 20 km. The basin provides advantageous conditions for the development of coal mining and coal consumption industries due to its favorable natural, geographical, and economic conditions. The basin is divided into three principal mining districts: Uong Bi, Dong Trieu, Hon Gai, and Cam Pha. Coal-bearing strata mainly belong to the Late Triassic Hon Gai Formation and contain multiple coal seams with thicknesses ranging from a few meters to more than 10 m. These seams are discontinuously distributed due to the strong influence of folding and faulting (Thang, 2016).

Structurally, the Quang Ninh coal basin has been affected by multiple compressional tectonic phases, resulting in the widespread development of fold and fault systems trending northwest-southeast and sub-latitudinal directions. syncline-shaped seams are commonly developed in most underground coal mines, such as Nam Mau, Trang Bach, Vang Danh, Ha Lam, Duong Huy, Khe Cham, and Mao Khe. These syncline-shaped seams vary considerably in scale, ranging from small structures with axial lengths of several hundred meters to large syncline-shaped seams extending over several kilometers. They are typically asymmetric and are frequently dissected by normal or reverse faults. Geological and hydrogeological conditions within synclinal areas are relatively complex. The bottom areas of synclinal-shaped seams often act as natural collectors of mine water and methane accumulation since they are located on low-lying topography and partially closed structural configuration. In addition, strata stress at the bottom areas of synclinal-shaped seams is generally higher than that in seam limbs, increasing the risk of roadway deformation, roof collapse, and other geotechnical hazards. These characteristics make synclinal areas representative targets for investigating the influence of fold structures on underground coal mining conditions in the Quang Ninh coal basin (Thang, 2016).

During exploration and mining activities in the Quang Ninh coal basin, syncline-shaped seams occur in a wide range of scales and morphological forms. Based on their geometry and size, the bottom areas of synclinal-shaped seams in the Quang Ninh region can be broadly classified into two principal types: (1) Bowl-shaped syncline seams , in which the intersection of the coal seam with a horizontal plane is circular or near-circular; (2) Trough-shaped syncline-shaped seams, in which the intersection of the coal seam with a horizontal plane is elliptical (Thang, 2016).

These two syncline-shaped seam types constitute the main objects of investigation in this study for comparative assessment, risk assessment, and the proposal of technical solutions tailored to the specific geometric characteristics of each type. Table 1 summarizes key information regarding their locations, bottom elevations, and current mining status (Thang, 2016). The data can be used to clarify the scale, spatial distribution, and morphological characteristics of syncline-shaped seams in underground coal mines in the Quang Ninh region.

Table 1. Compilation of synclinal structures in underground coal mines of the Quang Ninh region.

No.	Mine name	Syncline-shaped seam name	Remarks
1	Nam Mau	H.4; H.6; H.10	
2	Trang Bach	Cura Ngan	
3	Vang Danh	Dong Canh Ga	Khu Canh Ga
4	Binh Minh	Tay Bac Ha lam	
5	Thanh Cong	Ha Lam, Giap Khau, Cao Thang	
6	Ha Lam	Ha Lam	
7	Ha Rang	Da Bac, Dong La	
8	Duong Huy	Khe Tam	
9	Quang Hanh	Khoi Bac, Dong Bac, Khoi Nam	
10	Thong Nhat	Tay Nam, +18; 146 - 402	
11	Khe Cham III	Bang Nau, Cao Son	

3. Methodology

This study adopts an integrated methodological framework combining geological analysis, mining system evaluation, and comparative assessment to investigate the impacts of the bottom areas of synclinal-shaped seams on underground coal mining organization. The methodology establishes the link between synclinal-shaped seam geometry and mining layouts, operational constraints, and technical solutions applicable to different syncline-shaped seam types.

3.1. Data collection and study materials

The research is based on a comprehensive dataset obtained from representative underground coal mines in the Quang Ninh coal basin, with a particular focus on the Nam Mau mine. The collected materials include geological maps, cross-sections, seam correlation charts, mine opening schemes, panel layouts, production reports, and ventilation and drainage records. They were then validated with field observations and technical reports from mine operators to ensure consistency with actual mining conditions. The data integration process involved a systematic review of geological records and technical reports from 11 major underground coal mines across the Quang Ninh basin. This extensive primary dataset consists of numerous borehole logs and geological cross-sectional maps, covering the most active and complex coal-bearing zones. For each representative mine, our investigation focused on capturing a dense network of structural measurements, including axial plane orientations, limb dip angles, and fault distribution patterns. By synthesizing these multiple data sources, we ensured the representativeness of the synclinal geometries analyzed in this study, providing a robust empirical basis for the classification and mining solutions proposed.

In addition, the literature review of published studies and technical guidelines related to synclinal mining in underground coal mines from China, Poland, Germany, and Australia were implemented to provide a broader reference framework for comparison.

3.2. Classification of the bottom areas of synclinal-shaped seams characteristics

Based on geological data analysis, the bottom areas of synclinal-shaped seams were classified according to their geometric and mining-relevant characteristics, including syncline shape (closed, semi-closed, or elongated), size, seam dip variability, depth, and spatial relationship between adjacent seams. Particular attention was given to hydrological conditions, gas accumulation potential, and structural complexity, as these factors strongly influence mine opening design, ventilation, drainage, and production safety.

This classification serves as a foundation for assessing the impact of various syncline-shaped seam types on mining organizations and operational viability.

3.3. Analysis of mining organization at the bottom areas of synclinal-shaped seams

For each syncline-shaped seam type, the impacts on underground mining organization were analyzed with respect to the following aspects: mine opening and access methods, panel and longwall layout, mining system selection, transportation schemes, ventilation networks, and drainage arrangements. The analysis emphasizes the identification of critical constraints encountered at the bottom areas of synclinal-shaped seams, such as unstable seam dip, water accumulation, gas concentration, and increased coal losses due to protective pillars.

Operational performance indicators, including recovery ratio, coal loss rate, and adaptability to mechanization, were used to evaluate the effectiveness of existing mining practices.

3.4. Comparative analysis with international practices

A comparative analysis was conducted between mining practices at the bottom areas of synclinal-shaped seams in Quang Ninh and those reported for underground coal mines in China, Poland, Germany, and Australia. In which, mine opening strategies, level arrangements, degree of mechanization, pre-drainage measures, and coal recovery performance are the keys.

This comparison aims to identify technological gaps and potential improvements for the bottom areas of synclinal-shaped seams mining in Vietnam, particularly under conditions of increasing mining depth and geological complexity.

3.5. Methodological synthesis

The methodology was designed to establish a clear connection between synclinal-shaped seam geometry and underground mining organization. It allows us to determine critical technical constraints and the selection of appropriate mining solutions for each syncline-shaped seam type. The outcomes of this methodological framework directly support the analysis presented in the Results and Discussion section and provide a scientific basis for proposing optimized mining strategies for synclinal bottomsin underground coal mines. The methodological workflow consists of three main stages: (i) geological characterization and classification of synclinal structures; (ii) evaluation of mining organization based on operational indicators; and (iii) comparative synthesis to derive optimized mining strategies.

4. Results and Discussion

4.1. Structural Characteristics of Syncline-Shaped Seams in Underground Coal Mines of the Quang Ninh Region

The synthesis of geological documentation and mining data indicates that synclinal folds represent the dominant structural form in the Quang Ninh coal basin, where they are widely distributed across most operating underground coal mines. These syncline-shaped seams exhibit diverse scales and morphologies, ranging from elongated, linear forms trending in the northwest-southeast direction to nearly equidimensional or closed bowl-shaped structures. The synclinal axes are often discontinuous and segmented by fault systems that are either parallel or oblique to the fold axis, which significantly increases the structural complexity of coal seams. Most syncline-shaped seams in the study area are asymmetric, typically characterized by one steep limb and one gentler limb. The dip angle of the seam limbs varies markedly along the synclinal axis and with depth, resulting in substantial changes in apparent seam thickness and seam geometry. The bottom areas of synclinal-shaped seams commonly host thick coal seams with considerable geological reserves; however, they also represent zones with the most complex geological and technical conditions. Compared with anticlinal structures, syncline-shaped seam exert a stronger influence on mining organization because they simultaneously concentrate coal resources and act as convergence zones for mine water, mine gas, and in-situ stress. These findings are consistent with conclusions reported in numerous international studies conducted in coal basins with strongly developed fold structures.

A study of representative syncline-shaped seam at the Nam Mau, Trang Bach, Vang Danh, and Ha Lam mines shows that the bottom areas of synclinal-shaped seams have a number of important geo-technical features. First, these areas have complicated hydrogeological conditions because they are structurally low and the folds are relatively closed. This condition significantly increases the likelihood of water accumulation.. In many cases, water does not drain naturally along the seam but instead accumulates locally at the synclinal bottom, causing significant difficulties for roadway development and coal extraction. Second, gas conditions at the bottom areas of synclinal-shaped seams are generally less favorable than those on the seam limbs. The concave geometry of the structure promotes methane accumulation, particularly in bowl-shaped syncline seam thereby increasing the demands on ventilation systems and gas control measures. Third, in-situ stress at the bottom areas of synclinal-shaped seams tends to be higher as a result of fold geometry and increasing mining depth, which elevates the risk of roadway deformation, roof collapse, and face instability. These characteristics indicate that the bottom areas of synclinal-shaped seams are not only zones with high coal reserves but also areas with pronounced geotechnical risks, and therefore should be treated as specialized mining units in mine design rather than as simple extensions of seam limbs.

a) Nam Mau coal mine

Syncline-shaped seam H.4 is located in the western part of block T.IA. The synclinal axis trends southeast-northwest and dips toward the northeast, with an axial inclination ranging from approximately 60÷70^0. Both limbs of syncline-shaped seam H.4 are relatively gentle.

Syncline-shaped seam H.6 occurs in the northwestern part of block T.VI. Its axis trends northeastward and extends to the F400 fault. The axial plane dips toward the southeast, with an inclination of about 70÷80^0. The limbs of syncline H.6 are also relatively gentle.

Syncline-shaped seam H.10 extends from fault F357 toward the northwest of block T.IX, trending northwest-southeast. The axial plane dips to the southeast with an inclination of approximately 70÷80^0. The southeast limb has a dip angle of about 40÷50^0, whereas the northwest limb is gentler, with dip angles ranging from 25÷30^0.

b) Trang Bach coal mine

Cua Ngan syncline-shaped seam extends from block T.XXII eastward to block T.XXXVI in the eastern Trang Bach area and is dissected by the F433 fault. This structure is an open syncline-shaped seam with a slightly curved axial plane dipping southward at approximately 55÷70^0. The two limbs of the syncline-shaped seam are markedly asymmetric: the southern limb is very steep, with dip angles of about 70÷80^0, whereas the northern limb is gentler, with dip angles ranging from approximately 20÷25^0.

c) Vang Danh coal mine (Canh Ga area)

Dang Canh Ga syncline-shaped seam has a NE-SW trending axis, nearly coincident with panels T.10 and T.66B. The two limbs are asymmetric: the western limb has dip angles ranging from approximately 25÷35^0, whereas the eastern limb is steeper, with dip angles varying from about 35÷60^0.

d) Thanh Cong coal mine

The Giap Khau syncline-shaped seam occurs within the Central block and the Tay Binh Minh block. The syncline-shaped seam has an S-shaped axis trending roughly north-south and is intersected by the F6 and F14 faults. The Giap Khau syncline-shaped seam is relatively symmetrical, with the western limb dipping at about 25÷30^0 and the eastern limb dipping at approximately 30÷35^0.

The Cao Thang syncline-shaped seam occurs in the Tay Binh Minh block. It develops along a north-south trend and is structurally controlled by the F.HG and F6 faults. Both limbs are relatively gentle, with the western limb dipping approximately 20÷25^0 and the eastern limb dipping about 25÷35^0.

e) Ha Lam coal mine

The Ha Lam syncline-shaped seam is located approximately 650÷850 m from the Ha Lam shaft pillar. It is clearly expressed and structurally complex when observed from the surface facilities, geological cross-sections, or plan-view maps. This structure can be regarded as a composite synclinal zone, within which several anticlines and syncline-shaped seams of varying scales are developed. The axial dip of the fold ranges from about 65÷70^0 from east to west, and the structure extends in a north-south direction. The fold structure in the northern part is relatively stable, while toward the south, the synclinal features become progressively more pronounced.

f) Ha Rang coal mine

The Da Bac syncline-shaped seam trends in a northeast-southwest direction. The northwestern limb is relatively gentler, with dip angles ranging from approximately 35÷50^0, while the southeastern limb is steeper, with dip angles of about 35÷69^0.

The Dong La syncline-shaped seam is bounded by the Bắc Huy fault to the north, the F5 fault to the west, the F7 fault to the south, and the FD fault to the east. The synclinal axis trends southwest-northeast. The dip angles of both limbs vary from approximately 40÷70^0.

g) Duong Huy coal mine

The Khe Tam syncline-shaped seam is a large synclinal structure with an axis trending southwest-northeast, extending from Khe Tam through Khe

Cham to Mong Duong. Both limbs are relatively gentle, with dip angles of about 20÷30^0. The Khe Tam syncline-shaped seam is dissected by the FB and FC faults, as well as several minor faults, dividing it into multiple structural blocks. Numerous secondary folds occur on the limbs of the syncline-shaped seam, further increasing the structural complexity.

h) Quang Hanh coal mine

Northern block syncline-shaped seam is distributed in the central part of the northern block, with an axis trending approximately east-west, extending from the LK.2450-T.IB area to LK.2437-T.II. The axial plane gently dips northward (about 80^0). The limbs are asymmetric, with the northern limb dipping approximately 20÷25^0 and the southern limb dipping about 10÷15^0.

The Northeastern syncline-shaped seam is located in the northern part of the mine. Its axis trends nearly west-east, and the axial plane gently dips northward (about 80^0). The limbs are asymmetric, with the northern limb dipping 18÷20^0 and the southern limb dipping 35÷40^0. The synclinal axis is discontinuous and is offset by the F7 and F8 faults.

The southern block syncline-shaped seam extends along the southern part of the mine, from the LK.NNH12-T.VII area to LK.2443-T.IB. The synclinal axis trends west-east but is irregular and discontinuous due to displacement by the F11 fault. The axial plane gently dips northward (about 80^0). The limbs are asymmetric, with dip angles of approximately 40÷45^0 on the northern limb and 30÷35^0 on the southern limb.

i) Thong Nhat coal mine

Western syncline-shaped seam has an axis extending along the F.a fault. The western limb is relatively gentle, whereas the eastern limb is steep. Field observations from the G(4) seam in open-pit operations indicate that the eastern limb locally becomes nearly vertical, and the axial plane dips eastward.

The Southern syncline-shaped seam is a drag syncline-shaped seam associated with the F.C fault, with the axial plane plunging southward to southeastward. For the Thick Seam D(2) group, both limbs are relatively gentle, with dip angles ranging from approximately 10÷15^0 on the southern limb and 20÷25^0 on the northern limb.

+18 syncline-shaped seam is located in the southeastern part of area IVA. The synclinal axis trends approximately east-west (near latitudinal direction). The axial plane gently dips northward, and both limbs are gentle, with dip angles generally ranging from 15÷20^0.

146÷402 syncline-shaped seam is situated in the western part of the Lo Tri area, between T.IB and T.III. The synclinal axis trends northeast-southwest and gradually plunges eastward. Both limbs are gentle, with dip angles typically between 10^0 and 20^0.

j) Khe Cham III coal mine

The Bang Nau syncline-shaped seam is located in the northwestern part of the mine and covers an area of approximately 3 km^2. The synclinal axis trends nearly east-west, and the axial plane dips southward at an angle of about 75÷80°. The two limbs are asymmetric: the southern limb has dip angles ranging from 30÷60°, whereas the northern limb has been truncated by the L-L fault, with the remaining part exhibiting relatively gentle dips that decrease rapidly with depth.

The Cao Son syncline-shaped seam is the largest in the area, covering approximately 4 km^2. It is aligned with the principal structural trend of the Khe Cham coalfield and appears to be a continuation of the Bang Nau syncline-shaped seam. The synclinal axis develops predominantly in an east-west direction.

These geological characteristics do not directly determine mining performance but strongly condition the organization and effectiveness of underground mining operations, which are analyzed in the following sections. Overall, the analyzed synclines exhibit consistent characteristics, including asymmetric geometry, strong dip variability, and significant fault control, which collectively increase mining complexity.

The structural and geometric parameters of the investigated synclines across major mines in the Quang Ninh coal basin are synthesized in Table 2. These data highlight the prevalence of asymmetric folds and the significant influence of fault systems on seam continuity.

4.2. Influence of syncline-shaped seam on the Organization of Underground Coal Mining

Syncline-shaped seams, particularly their bottom parts, create unfavorable geological and mining conditions that exert direct and combined impacts on the organization of underground coal mining. The bottom areas of synclinal-shaped seams are characterized by concave, closed, or semi-closed structures, which is in contrast to seam limbs with relatively stable seam geometries. These features substantially increase the complexity of mine opening, longwall panel arrangement, coal transportation, ventilation, and drainage systems. Figure 1 presents a conceptual block diagram illustrating the chain of influences from geological and mining conditions to mining organization and the corresponding technical solution requirements. The differences between the cause-and-effect relationships between the structural characteristics of the bottom areas of synclinal-shaped seams and the resulting technical consequences in underground coal mining can be seen clearly.

From a geological perspective, the synclinal bottom represents the zone where unfavorable variations in coal seam conditions are most strongly concentrated. Seam dip angles vary significantly and irregularly in both strike and dip directions, making it difficult to maintain a stable longwall orientation along the seam. Frequent adjustments of the cutting direction are required to adapt to this variability when it limits the feasibility of fully mechanized mining systems. Such modifications lead to continuous changes in longwall length and support layout, thereby increasing operational complexity. In addition, strata stability at the bottom areas of synclinal-shaped seams is generally poorer than at seam limbs due to the combined effects of folding and faulting.

This condition increases the risk of roadway deformation, face instability, roof falls, and longwall collapse. Regarding the mine environment, the bottom areas of synclinal-shaped seams are the lowest zones within the mining space.

Table 2. Geological and structural characteristics of representative synclines in the Quang Ninh coal basin.

Mine name	Syncline name	Axial plane / trend	Limb characteristics (Dip angles)	Associated structural features
Nam Mau	H.4, H.6, H.10	SE-NW to NE; Axial dip 60÷80^0	Asymmetric; Limbs range from gentle (25÷30^0) to moderate (40÷50^0)	Intersected by faults F400 and F357
Trang Bach	Cua Ngan	E-W; Axial plane dips S (55÷70^0)	Strongly asymmetric: S limb (70÷80^0), N limb (20÷25^0)	Open syncline dissected by F433 fault
Vang Danh	Dong Canh Ga	NE-SW	Asymmetric: W limb (25÷35^0), E limb (35÷60^0)	Axis coincides with panels T.10 and T.66B
Thanh Cong	Giap Khau, Cao Thang	N-S; S-shaped axis	Relatively symmetrical to gentle (20÷35^0)	Controlled by faults F6, F14, and F.HG
Ha Lam	Ha Lam	N-S; Axial dip 65÷70^0	Progressive structural complexity from North to South	Composite synclinal zone with secondary anticlines
Ha Rang	Da Bac, Dong La	NE-SW	Moderate to steep (35÷70^0)	Bounded by faults Bac Huy, F5, F7, and FD
Duong Huy	Khe Tam	SW-NE	Gentle limbs (20÷30^0)	Segmented by FB, FC faults and secondary folds
Quang Hanh	Northern, NE, Southern	W-E; Axial plane dips N (~80^0)	Asymmetric: N limb (18÷45^0), S limb (10÷40^0)	Discontinuous axis due to F7, F8, and F11 faults
Thong Nhat	Western, Southern, +18, 146-402	E-W to NE-SW	Variable: Gentle (10÷25^0) t o locally vertical on E limb	Includes drag synclines associated with F.a and F.C faults
Khe Cham III	Bang Nau, Cao Son	E-W; Axial plane dips S (75÷80^0)	Asymmetric: S limb (30÷60^0), N limb truncated by L-L fault	Large scale structures covering 3÷4 km^2

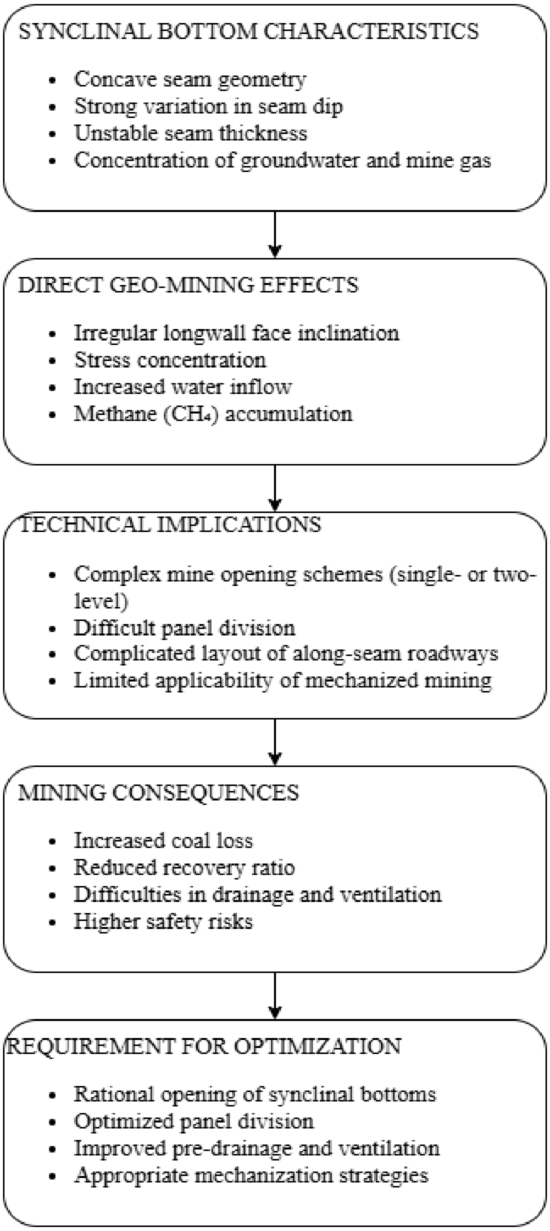

Figure 1. Conceptual block diagram illustrating the causal chain of synclinal-bottom characteristics, their geo-mining effects, technical implications, and mining consequences in underground coal mines.

Mine water naturally tends to collect in this area. Similar observations have been reported in synclinal mining areas under high-confined aquifers, where water inflow is strongly controlled by structural closure and hydrogeological connectivity (Luo et al., 2025).

If gate roadways are arranged at the same elevation as or higher than the bottom areas of synclinal-shaped seams, gravity drainage becomes ineffective, resulting in localized water pooling within longwall faces and development roadways. This increases drainage costs due to the need for forced pumping and directly affects working conditions and operational safety. Moreover, the closed or semi-closed structural configuration of the bottom areas of synclinal-shaped seams promotes the accumulation of mine gases, particularly methane (CH_4). This phenomenon is consistent with previous studies indicating that tectonic complexity enhances methane enrichment in structurally confined zones (Ye et al., 2023).As a result, ventilation becomes more complex, requiring numerous airflow control structures such as regulators, overcasts, and extended return airways. Figure 2 illustrates the specific impacts of the bottom areas of synclinal-shaped seams on underground mining organization, including mine opening design, longwall layout, mechanization potential, ventilation, drainage, and coal losses.

Another notable consequence of mining at the bottom areas of synclinal-shaped seams is the high level of coal loss. Owing to the concave and closed geometry of syncline structures, the layout of along-seam roadways and protective pillars at the bottom areas of synclinal-shaped seams often cannot closely follow the optimal seam boundaries, resulting in irregular coal remnants that are difficult to recover. In many cases, when conventional rectangular panel subdivision schemes are applied, a significant portion of coal resources at the bottom areas of synclinal-shaped seams remains unextractable, leading to a lower recovery factor compared with the two seam limbs. To clarify the differences between mining conditions at the bottom areas of synclinal-shaped seams and at the seam limbs, Table 3 presents a comparison of the main geological characteristics and their respective impacts on underground coal mining organization.

The comparative results indicate that, while seam limbs exhibit relatively stable geometries that are favorable for arranging longwall panels along the seam strike, facilitating gravity-assisted drainage and simple ventilation schemes, the bottom areas of synclinal-shaped seams concentrate multiple unfavorable factors simultaneously.

The combined effect of these factors renders mining organizations at the bottom areas of

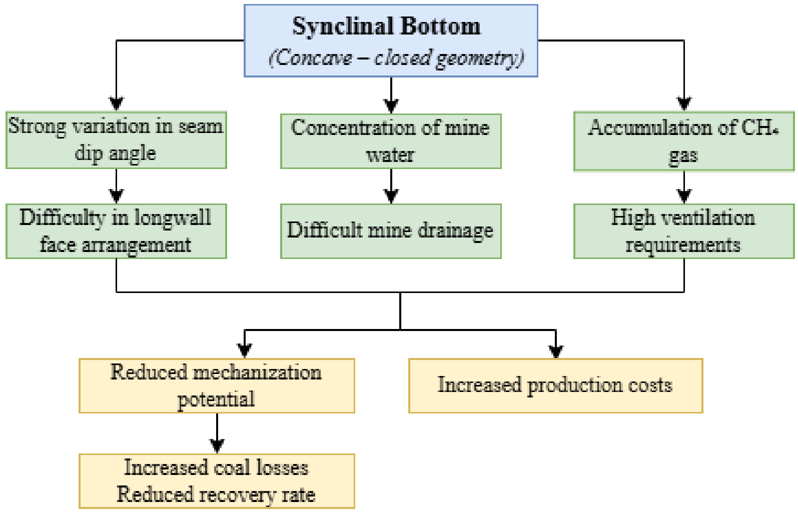

Figure 2. Conceptual diagram illustrating the influence of the bottom areas of synclinal-shaped seams on underground coal mining organization.

Table 3. Comparison of geological characteristics and their impacts on underground mining organization between the bottom areas of synclinal-shaped seams and the seam limbs.

Criteria	The bottom areas of synclinal-shaped seams (Quang Ninh)	Seam limbs	Impact on mining operations
Seam geometry	Concave, closed, or semi-closed	Relatively stable	Difficult to arrange longwall panels along the seam strike
Seam dip angle	Highly variable and uneven	Slightly variable	Limits the application of mechanized mining
Hydrogeological conditions	Concentration of mine water	Favorable natural drainage	Increases drainage costs
Gas conditions	Prone to methane (CH_4) accumulation	Better gas dispersion	Requires complex ventilation systems
Strata stability	Strong deformation	More stable	Increases the risk of roof falls
Coal loss	High	Lower	Reduces coal recovery factor
Feasibility of mining system organization	Complex, low flexibility	Favorable, stable	Influences the selection of mining systems and technologies

synclinal-shaped seams a complex engineering problem, requiring tailored solutions for mine opening, panel subdivision, and mining technologies adapted to specific types of synclinal structures. At underground coal mines in the Quang Ninh coalfield, particularly at Nam Mau Mine, the mining system commonly applied at the bottom areas of synclinal-shaped seams is the strike-oriented longwall panel subdivision system, combined with drilling-and-blasting techniques and roof support using mobile steel frames or single hydraulic props. These technologies have been employed for an extended period and remain compatible with the current technical conditions and level of mechanization of the mines. However, mining operations at the bottom areas of synclinal-shaped seams frequently encounter significant difficulties, including unstable longwall face dip angles, continuously varying face lengths, and challenges in maintaining straight longwall alignment along the seam strike.

These issues reduce production efficiency and limit the feasibility of fully mechanized mining. In particular, at basin-shaped the bottom areas of synclinal-shaped seams, mine water tends to accumulate in central areas, posing substantial challenges to drainage operations and increasing the risk of sudden water inrush events.

4.3. Selection of synclinal types for proposing mining solutions

As can be seen in Section 4.2, it is evident that not all synclinal structures impose the same level of technical constraints and operational risks. Variations in synclinal geometry, scale, and geological-mining conditions directly govern the feasibility of mine opening schemes, panel subdivision strategies, and the applicability of specific mining technologies. In particular, the shape of the synclinal bottom (e.g., narrow, wide, or basin-shaped), its spatial relationship with adjacent seams, and associated hydrogeological and gas conditions exert a decisive influence on drainage efficiency, ventilation stability, and longwall layout. Consequently, treating all the bottom areas of synclinal-shaped seams using uniform opening and mining approaches may increase coal losses, reduce safety margins, and suboptimal production performance. Therefore, the classification and selection of syncline-shaped seam types is a necessary prerequisite for proposing targeted, safe, and efficient mining solutions. An appropriate combination of mine opening methods, reserve subdivision schemes, and mining technologies can be systematically developed and matched to each synclinal type by identifying representative synclinal categories based on structural geometry and mining conditions.

4.3.1. Classification of the bottom areas of synclinal-shaped seams based on morphological characteristics and scale

Based on the synthesis of morphological characteristics, spatial scale, and dip variability, this study establishes a systematic Classification Framework to guide mining operations in the Quang Ninh coal basin. This framework categorizes syncline-shaped seams into three distinct types, each associated with specific technical constraints and optimized mining strategies (Table 4).

The first group comprises large-scale the bottom areas of synclinal-shaped seams with basin-shaped or fully enclosed elliptical geometries. In this category, syncline-shaped seams are characterized by relatively flat bottom areas but extensive lateral dimensions, which are favorable conditions for the accumulation of mine water and methane. Within such syncline-shaped seams, the dip angle both along strike and down dip of coal seams often exhibits pronounced variations, making highly complex structural conditions.

Table 4. Classification framework for synclinal-shaped seams and corresponding mining solutions.

Syncline category	Morphological characteristics	Key technical constraints	Recommended mining strategy
Type I: large-scale basin	Extensive lateral scale (>1 km); fully enclosed or elliptical geometry; flat but irregular bottom.	High risk of water/gas accumulation; extreme dip variability; high coal loss in conventional layouts.	Multi-level access: combined cross-cuts and inclined roadways; Independent blocks: Strike-oriented longwall with enhanced pre-drainage.
Type II: medium-scale semi-enclosed	Semi-enclosed geometry; maintained hydraulic connectivity with seam limbs.	Localized depressions; haulage and roadway maintenance difficulties along the axis.	Flexible access: Integrated development from both bottom and limbs; Adaptive longwall: Variable face lengths to match morphology.
Type III: small-scale linear	Narrow, linear, or near-isometric forms; limited spatial influence.	Coal losses concentrated in protective pillars near the synclinal axis.	Integrated mining: Incorporation into existing districts; conventional methods with minor orientation adjustments.

This type of synclinal bottom poses significant challenges to drainage and ventilation organization and is commonly associated with high coal losses if inappropriate panel subdivision schemes are adopted. Without specialized mine opening and subdivision solutions, large basin-shaped syncline-shaped seam present one of the most unfavorable settings for underground coal extraction.

The second group includes medium-scale bottom areas of synclinal-shaped seams with semi-enclosed geometries, in which part of the synclinal bottom maintains hydraulic and ventilation connectivity with the adjacent seam limbs. Compared with large enclosed syncline-shaped seam, drainage and ventilation conditions in this group are relatively more favorable. Nevertheless, haulage organization, longwall layout, and roadway maintenance are difficult if local depressions and irregularities along the syncline-shaped seam axis occur. These syncline-shaped seams require flexible mine opening and subdivision strategies to mitigate localized adverse conditions while maintaining overall production stability.

Small-scale the bottom areas of synclinal-shaped seams with narrow, linear, or near-isometric geometries are typical for the third group. Such syncline-shaped seams typically extend along a dominant structural direction and have limited spatial influence on mining operations. Although their overall impact on underground mining organizations is relatively minor compared to larger syncline-shaped seams, careful adjustment of longwall orientation and panel geometry is still necessary to control coal losses, particularly in protective pillars near the synclinal axis. When properly managed, small the bottom areas of synclinal-shaped seams can often be mined using conventional opening and extraction methods with only minor technical modifications.

The comparative results presented in Table 5 reveal that the technical feasibility and operational risks associated with synclinal bottoms are strongly governed by their morphological scale and degree of structural closure. A clear gradient can be observed from Group 1 to Group 3, reflecting a transition from favorable large-scale mining conditions to highly constrained and risk-prone environments.

For Group 1 (large-scale basin synclines), the extensive lateral continuity and relatively stable geometry enable the development of systematic panel layouts and gravity-assisted drainage systems. As a result, these structures exhibit high mechanization potential and optimized resource recovery. However, these advantages are conditional upon the implementation of appropriate multi-level access and pre-drainage strategies. Without such designs, the same large-scale geometry may instead amplify water and gas accumulation risks.

In contrast, Group 2 (medium-scale semi-enclosed synclines) represents an intermediate

Table 5. Comparative analysis of technical indicators and operational risks among the proposed syncline groups.

Comparative criteria	Group 1 (large-scale/open basin)	Group 2 (medium-scale/semi-enclosed)	Group 3 (small-scale/linear)
Drainage feasibility	High efficiency: Primarily relies on natural gravity-driven drainage.	Moderate: Requires a combination of gravity and forced pumping.	Low: high risk of localized water pooling; requires intensive forced pumping.
Mechanization potential	High: suitable for long, stable longwall faces with high-level mechanization.	Moderate: requires adaptive/flexible face lengths to handle geometric variability.	Low: limited by narrow geometry; primarily relies on conventional /semi-mechanized methods.
Gas accumulation risk	Low: favorable for establishing effective ventilation networks.	Moderate to high: Prone to methane accumulation in semi-closed zones.	Very high: concentrated gas in confined spaces; requires strict airflow control.
Resource Recovery	Optimized: large lateral scale allows for systematic panel layouts.	Variable: Influenced by the complexity of semi-enclosed boundaries.	Challenging: significant coal losses in protective pillars along the synclinal axis.

condition in which both favorable and unfavorable factors coexist. Partial hydraulic connectivity with seam limbs improves drainage compared to closed basins, but local depressions and geometric irregularities introduce operational instability. Consequently, mining systems in this group must balance mechanization with flexibility, requiring adaptive longwall layouts and hybrid drainage solutions.

The most critical conditions are observed in Group 3 (small-scale linear synclines), where confined geometry, limited spatial continuity, and structural closure significantly restrict mining operations. These conditions promote localized accumulation of mine water and methane, increase reliance on forced pumping, and result in substantial coal losses due to protective pillar requirements. From an operational perspective, these synclines are generally unsuitable for independent large-scale development and are more effectively exploited through integration into existing mining districts.

Overall, Table 5 demonstrates that synclinal morphology is not merely a geological descriptor but a primary control on mining system design, operational risk distribution, and resource recovery efficiency. The classification-based differentiation provides a practical decision-support framework for selecting appropriate mining strategies under varying geological conditions.

The significance of these categorical differences lies in the fundamental shift required for each group's mining strategy. For Group 1, the technical focus is on maximizing production scale through advanced mechanization, as the extensive and relatively stable geometry permits large-scale infrastructure. In contrast, for Group 2, the priority shifts toward operational flexibility, requiring drainage systems and roadway layouts that can adapt to semi-closed configurations. The most critical distinction is observed in Group 3, where the 'significance' of the classification is the recommendation against independent development. Due to high safety risks and potential coal losses, these zones should be integrated into existing mining districts to ensure both economic viability and ventilation safety.

4.3.2. Orientation for selecting mining solutions according to different types of syncline-shaped seams

For large syncline-shaped seam with a closed basin geometry (Group 1), mining solutions should prioritize two-level or multi-level access systems. They should be able to combine cross-cut drifts with upper drifts or inclined rock roadways to ensure effective ventilation and gravity-driven drainage. Mine panel division should be organized into independent mining blocks located at the bottom areas of synclinal-shaped seams, while minimizing the use of conventional rectangular longwall panels in order to reduce coal losses. The appropriate mining technology is a strike-oriented longwall mining system with panel subdivision, combined with partial mechanization and strengthened measures for controlling mine water and gas.

For medium-sized syncline-shaped seam with a semi-closed geometry (Group 2), more flexible access schemes can be applied to integrate development from both the bottom areas of synclinal-shaped seams and the two seam wings. Longwall layout should preferentially follow the strike direction of the seam, with adaptive adjustment of longwall face length to accommodate variations in the bottom areas of synclinal-shaped seams morphology. Where geological and technical conditions permit, a higher level of mechanization can be gradually introduced compared to Group 1.

For small syncline-shaped seams of linear or isometric types (Group 3), mining solutions can be largely similar to those applied in the seam wings, with localized adjustments in roadway development and longwall layout. Exploitation of these syncline-shaped seams should be integrated into existing mining districts to minimize the amount of preparatory roadway development and reduce coal losses.

4.3.3. Technical and production organization implications

The analysis results indicate that using syncline-shaped seam classification as the basis for selecting mining solutions enhances proactiveness in production organization while significantly reducing technical risks related to mine water, mine gas, and strata stability. Rather than applying a rigid mining model uniformly to all syncline-shaped seams, the classification-based approach enables underground coal mines in the Quang Ninh coalfield to optimize access schemes, mine block division, and the selection of mining technologies in accordance with the specific geological and mining conditions of each area.

4.4. Discussion

The research results confirm that syncline-shaped seams, particularly the bottom areas of synclinal-shaped seams, are not only zones concentrating significant coal reserves but also mining units associated with a high level of technical risk in underground coal mining. Compared with the two seam wings, the bottom areas of synclinal-shaped seams exhibits pronounced combined disadvantages in terms of seam geometry, hydrogeological conditions, mine gas, and strata stability, which directly govern access schemes, mine block division, and mining efficiency. These findings are consistent with international studies conducted in China, Poland, Germany, and Australia, where concave fold structures are commonly regarded as special mining targets and are addressed using dedicated technical solutions such as multi-level access systems, pre-drainage prior to mining, and high levels of mechanization (Xu et al., 2022; Zdechlik et al., 2022). However, the present study indicates that under the conditions of underground coal mines in the Quang Ninh coalfield, the integrated application of such advanced solutions is constrained by relatively low mechanization levels and more complex geological conditions, particularly the high density of faults and strong variations in seam dip angles within syncline-shaped seam zones.

Comparative analysis among mines in the Quang Ninh coal basin shows that syncline-shaped seam areas developed from the bottom areas of synclinal-shaped seams, with appropriately designed gravity-driven drainage systems, generally achieve higher mining efficiency and reduced risks of water-gas incidents. In contrast, closed-basin syncline-shaped seams or syncline-shaped seams with bottoms located below the main roadway systems often face severe drainage difficulties, which increase operating costs and greater resource losses. Clearly, the role of selecting access schemes tailored to the specific morphology and scale of each syncline-shaped seam is critical in this case. From a methodological perspective, the study demonstrates the value of an approach that integrates fold structure analysis with underground mining organization. It allows us to early identify the technical constraints and select appropriate mining solutions for different syncline-shaped seam types. This approach is particularly significant in the context of increasing mining depth in the Quang Ninh underground coal mines, where geological conditions become progressively more complex, and safety margins are increasingly reduced.

Nevertheless, the study still has certain limitations. The analyses are mainly based on technical assessment and practical experience, without in-depth quantitative modeling of mine water and gas flow, nor a comprehensive evaluation of the economic efficiency of individual mining solutions. These aspects represent important directions for future research to further improve the scientific basis for mine design and production organization in the bottom areas of synclinal-shaped seams areas.

5. Conclusion

This study provides a comprehensive characterization of synclinal structures in the Quang Ninh coal basin from a mining engineering perspective. The primary contribution of this research is the establishment of a systematic classification framework that links synclinal morphology (Large-basin, Medium-semi-enclosed, and Small-linear) with specific technical requirements. Our findings demonstrate that treating synclinal bottoms as specialized mining units rather than simple extensions of seam limbs is essential for mitigating geotechnical risks, such as water inrush and gas accumulation. The proposed framework serves as a decision-support tool for mine designers to optimize access schemes and select appropriate extraction technologies. By adopting these tailored solutions, underground coal mines can significantly improve resource recovery factors and operational safety in increasingly complex and deep mining environments. The proposed framework is expected to be transferable to other coal basins with similar structural complexity, contributing to more efficient and safer underground mining practices.

Acknowledgements

During the preparation of this work, the authors used ChatGPT to check spelling and grammar and improve the readability of the publication. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication. The authors gratefully acknowledge Dr. Vu Dinh Trong for his careful review and valuable assistance in refining and standardizing the English language of this manuscript.

Contributions of authors

Thang Hung Hoang – Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing.

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