INTRODUCTION

Recently, concerns regarding coal resource waste and safety mining have grown worldwide. The no-pillar mining method without advance tunneling, known as the N00 longwall mining method, represents a rational alternative in this regard. Since the 20th century, coal mining technology has undergone long-term development in China. The mining methods used in China’s coal industry can be classified into three types: longwall mining, gob-side entry retaining, and N00 longwall mining. The longwall mining method, which originated in Britain during the early 18th century, was first used in China in the 1930s and has been developed for approximately 90 years. It has become one of the landmark achievements in the field of coal mining in China. However, a large coal pillar measuring 20-50 m and double advance tunneling roadways should be set up before stopping a working face when using this mining method. This results in low coal recovery rates and mining productivity. Hence, the contradiction between this mining method and China’s energy characteristics has become more prominent.

Validation study of no-pillar mining method without advance tunneling: A case study of a mine in China

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Abstract

Studies regarding the reuse of a gob-side roadway formed by the N00 longwall mining method are scarce. To investigate the mine pressure behavior characteristics during roadway reuse, the anchor cable force, roof-to-floor deformation, and working resistance of the hydraulic support obtained from the verification working face were analyzed. Test results show that the influence range of the mining-induced pressure was 0-90 m in front of the working face. The ratios of the first and periodic weighting steps between the entry-retaining and non-roof-cutting sides were 20.25 and 1.94, respectively. However, the ratios of the ground pressure strengths at the two sides were 1.07 and 1.31, respectively. The results indicate that the monitored roadway can be classified into three deformation zones based on the severity of the mine pressure behavior: large, intermediate, and creep. The main roof between the adjacent working faces exhibited a failure type comprising the “O-X” and “O-Y” states, which resulted in an unconventional mine pressure behavior. This study provides insights into the N00 longwall mining method as well as important guidance for tackling similar geological conditions when using this mining method.

KEYWORDS
gob-side entry retaining, longwall mining, mining rock mechanics, no-pillar mining method without advance tunneling, roof-cutting and pressure-relief technology
The gob-side entry retaining technique was developed in the 1930s to minimize coal pillar preservation and reduce the roadway driving rate.5-6 This method yielded significant achievements compared with the traditional longwall mining method, that is, one-roadway tunneling is reduced and no-coal pillar reservation between panels is realized. This retaining technique not only affords significant economic benefits and increases the coal recovery rate but also mitigates the environmental pollution of waste rock.7 However, the implementation of gob-side entry support is challenging in this technique and should be handled accordingly. The supporting materials used in the technique primarily include flexible-hard materials, flexible concrete formworks, high-water filling materials, and bag filling materials.8-11 Furthermore, the failure characteristics of the surrounding rock under different conditions, such as high roof pressure, large deformation of gob-side entry, and failure of gob-side walls, should be prioritized.12-14

To address the aforementioned challenges and simultaneously ensure that the gob-side entry-retaining technique remains effective, an innovative no-pillar mining method, known as the N00 longwall mining method, was proposed in China in 2016. Recently, this method was applied to thick coal seams and deep-burial coal seams.15-19 Similar to the traditional gob-side entry retaining technique, the issues of stability and failure characteristics of the surrounding rock and experimental methods have garnered the attention of researchers. Research methods such as theoretical analysis, numerical testing, and similarity simulations are the mainstream methods for investigating mining techniques.16-22 Recently, key technologies, the roadway formation process, equipment matching, control countermeasures for automatically formed entry, and application assessments have garnered significant attention, and relevant studies have yielded meaningful results.23,24

Because of the significant association among the three aforementioned mining methods, their advantages and disadvantages must be analyzed. The roadway layouts of the three mining methods are shown in Figure 1.

A typical strategy used to excavate coal resources is the conventional longwall mining method. Whenever coal is mined, two roadways must be tunnelled in advance on both sides of a panel. Moreover, a coal pillar with a width of 20 m or higher must be reserved between the panels. It is noteworthy that such coal pillars are regarded as unusable coal resources and often remain underground for a long period. Although this technology offers safety and is mature, it also presents disadvantages such as complex processes, non-optimal use of resources, and substantial investments. Compared with the conventional longwall method, the gob-side entry retaining technique successfully reduces roadway driving and obviates the need for coal pillars between panels. Hence, the recovery rate of coal resources and the excavation rate of the roadway can be improved and reduced, respectively, using this strategy. However, when mining a working face, broken waste rocks, concrete, or high-water materials can be filled along the edge of the goaf as roadside support for the extremely high mining pressure. The main obstacles to this approach are the roadside support along the gob side and the strong pressures induced by mining.

Unlike the gob-side entry retaining technique, the N00 longwall mining method dispenses with roadway driving between panels before mining a coal face. In addition, three-machine linkages for excavating mines and four-machine linkages for forming gob-side entries have been used to ensure the stability of the mining space. In summary, this mining technology has promoted the development of China’s coal industry and has enabled significant developments in terms of equipment innovation, basic theory, and test methods. It is gradually becoming a crucial technique for the coal mining industry in China and is beneficial for promoting more knowledge regarding coal mining intelligence.

Generally, an automatically formed entry should be used not only in the entry retaining stage but also during adjacent coal face mining. The reuse of automatically formed entries, which is a fundamental aspect of the N00 longwall mining method, has not been investigated comprehensively, that is, only a few studies have investigated the typical associated issues. Hence, this study was conducted to investigate the stability of an automatically formed roadway and the ground pressure of a working face during the reuse stage. The key challenge is to unravel the structural basis such that the supernormal mechanical behavior can be explained based on the reuse condition. To investigate the aforementioned issues more efficiently, the stability of an automatically formed roadway was investigated in this study based on the anchor...
Cable force and roof-to-floor deformation. Additionally, the mechanical characteristics of the working face were investigated based on the hydraulic support pressure. A low mining pressure and a stable mining space during mining were achieved in the test, which facilitated the investigation of a field test case for the N00 longwall mining method. The results will address the dearth of relevant research and provide important guidance for tackling similar geological conditions when using the N00 longwall mining method to excavate coal resources. This is important for conserving coal resources and ensuring safe mining.

2 | METHODOLOGY

2.1 | Experimental conditions

The S12012 working face is the first test longwall face mined using the N00 longwall mining method in China. Roadway formation has been achieved successfully in a previous project. As the only adjacent working face of S12012, the S12013 longwall face could be an excellent candidate to validate the N00 mining method because of the similar geological conditions of these working faces. Therefore, the first industrial test for reusing the automatically formed entry based on the N00 longwall mining method was conducted on the S12013 working face in Ningtiota Coal Mine in Shenmu County, Shaanxi Province, China. The roadway layout and lithologies of the coal seam, roof, and floor are shown in Figure 2.

The strike length of the S12013 working face is 1781.9 m, and its tendency length and mining depth are 333.4 m and 114-172 m, respectively. The coal seam is stable, and the coalbed pitch is almost horizontal. Based on geological investigations, it was inferred that the coal seam has a simple geological structure. The main roof of the coal face comprises medium or fine sandstone and was 3.21-16.58-m thick; the immediate roof is siltstone and 0-1.28-m thick; the immediate floor is siltstone or sandy mudstone and 12.92-25.22-m thick; and the main floor is fine sandstone or siltstone and 3.20-7.24-m thick. Furthermore, the thickness of the coal seam is 3.80-4.21 m, which is similar to the thickness of the S12012 working face.

This coal mine has been identified as a low-gas mine, based on the method for identifying the gas grade in coal mines stipulated by National Energy Administration. Moreover, the...
absolute gas emission rate and relative gas emission rate are 2.32 and 0.06 m$^3$/t, respectively. Because the spontaneous combustion period of the coal seam is only 30 days, the spontaneous combustion grade has been classified as grade I, that is, the coal seam can easily combust spontaneously. In terms of hydrogeology, the water-bearing characteristics in the area investigated are dominated by fissure water, and the hydrogeological conditions are simple.

### 2.2 Experimental methods and procedures

#### 2.2.1 Supporting method for automatically formed roadway

The structure of the roadway formed automatically using the N00 longwall mining method differs from that of a traditional roadway, in that the former includes an arc-shaped solid coal wall and a granular side. Based on the roadway section design, the width and height of the automatically formed roadway were 6738 and 3750 mm, respectively. To support the automatically formed roadway effectively, we designed a special support method, as shown in Figure 3.

Considering that significant deformation might occur on the roof when using the N00 mining method, a constant-resistance and large-deformation anchor cable (CRLD cable) was adopted to prevent deformation and failure of the roof. The CRLD anchor cable is favored for its mechanical properties such as a high preload, high constant supporting force of 200-500 kN, high elongation of approximately 1000 mm, and strong energy-absorbing ability. In this study, the constant resistance force was set to 320 kN. The structure and operating principle of the CRLD anchor cables are illustrated in Figure 4.

Because the coal seam has a shallow burial depth and a low floor stress, we used concrete to reinforce the floor.

The automatically formed roadway comprised two sides, that is, the solid coal and granular sides. The formation of the solid coal side of the entry differs from that corresponding to the conventional method, in that the coal side is cut using a coal mining machine into an arc shape. To enable the use of a coal cutter to form an arc-shaped solid coal wall, we improved the scraper conveyor and coal cutter in advance. When the coal cutter was traversing to the scheduled area of the roadway, the roller moved past the tail of the improved scraper conveyor to cut the upper and lower sections of the coal seam chronologically, which is consistent with the procedure established for the machine. The excavated coal was automatically loaded by the scraper conveyor. The traversal track of the improved coal cutter is shown in Figure 5. Because the solid coal wall was cut by the roller derived from the rocker arm, the obtained shape was an arc. Compared with a straight wall, an arc-shaped wall is more stable. An arc-shaped wall can not only prevent rib spalling but can also maintain a favorable stress environment. For safety, we adopted a glass fiber-reinforced plastic bolt to reinforce the roadway.

The granular side of the roadway was formed using a roof-cutting and pressure-relief technique. It was supported using a custom-developed caving gangue support technology that included gangue supports, slidable U-steel bolts, and wire mesh. The main function of the gangue support was to provide supporting resistance to the roof and gangue. It was designed to resist the lateral impact load from the gob in the event of gangue collapse and to provide vertical high-strength temporary support resistance to prevent the roof from being deformed significantly during dynamic-pressure situations.

#### 2.2.2 Monitoring method for automatically formed roadway and working face

**Monitoring method for automatically formed roadway**

To determine the deformation characteristics of the surrounding roof in the automatically formed roadway during reuse,
a remote online monitoring system was used to analyze the supporting force of the anchor cable and the roof-to-floor deformation. Five observation stations were set 638-778 m away from the cutting location, and the space between the monitoring sections was 20-50 m. A roof-to-floor deformation monitor, which was a laser range finder used for supervision, was installed in the middle of the roadway. Each observation station was equipped with one measuring point. For the anchor cable force monitor, each station was equipped with two dynamometers, which were located on the side of the arc wall and the middle of the roadway. Monitor stations #1 and #2 were located at 728 and 778 m in front of the cutting location, respectively. The monitoring scheme is illustrated in Figure 6. A manual measurement method was used to monitor the effect of mining on the deformation of the observed roadway.

**Monitoring method for working face**

To determine the initial weighting and periodic weighting laws at different positions of the S12013 working face and then analyze the mine pressure behavior law, the KJ440 monitoring system for roof pressure was used to monitor the working resistance of the hydraulic support. We arranged 39 working resistance monitoring stations on 195 hydraulic supports, and the space between the monitoring stations was 1-7 hydraulic supports. The working resistance was set to 10,000 kN for the hydraulic support. Moreover, the data acquired by the monitoring system could be transferred to the surface control center via a detection substation installed on an underground equipment train. A schematic illustration of the S12013 working face is shown in Figure 7.

3 | RESULTS

The main findings regarding the anchor cable support force, roof-to-floor deformation, and pressure characteristics of the working face are summarized in this section. Furthermore, some of the main characteristics of the mechanical phenomena that occurred during the reuse of the automatically formed entry are analyzed.

3.1 | Anchor cable support force

Figure 8 shows the test data obtained from the anchor cable force monitor. The relationship between the anchor cable support force and time can be determined from the figure. For observation stations #1 and #2, the anchor cable support force in the middle of the roadway and at the cambered side increased with time. However, the increasing range of the anchor cable force yielded significantly different results. The data obtained by observation station #1 indicate that the anchor cable force in the middle of the roadway and cambered side increased by 15 and 14 kN, respectively. Similarly, the anchor cable force recorded by observation station #2 increased by 6 and 13 kN, respectively. Compared with that on the arc side, the support force of the anchor cable in the middle of the roadway was higher. The difference in the support forces of the anchor cable represents a similar law numerically.
Mining was performed on the S12013 working face on April 18, 2019. The deformation of the automatically formed roadway converged prior to the mining of the S12013 working face, with average gradients of 0.16 and 0.10 mm/day based on the observed data from monitor stations #1 and #2, respectively. As shown in Figure 9, the roof-to-floor deformation rate remained stable with the advancement of the S12013 working face, the average gradient of which was 0.16 and 0.14 mm/day for monitor stations #1 and #2, respectively. This is similar to the data prior to mining. Furthermore, to
analyze the characteristics of the roof-to-floor deformation more effectively, the curves were fitted using a linear fitting method. The $R^2$ values of the data recorded by stations #1 and #2 were 0.939 and 0.891, respectively, indicating that the deformations were flat. According to field observations, roof breakage or spalling ribs were not present in the solid coal wall. In addition, the advancing distance of the working face, as recorded on June 30, 2019, was 616.60 m.

The mining-induced pressure affected the roadway in front of the working face, that is, irregular roadway deformations were observed. Figure 10 shows that the part of the roadway within 90 m in front of the working face was affected significantly by the excavation, particularly in the range of 0-60 m. This is attributable to the roof of the roadway, which was perturbed significantly by the movement of the adjacent goaf roof and tended to propagate with the adjacent goaf roof. Compared with the middle of the roadway in the range of 0-60 m, the solid cambered side of the observed roadway was severely affected by mining, based on the data of roof-to-floor deformation increment. However, the effect of the surrounding rock of the roadway at the gangue side was marginal. Meanwhile, the roof-to-floor deformation increment law in the range of 60-130 m in front of the working face was significantly different from that in the range of 0-60 m. As shown in Figure 10, the deformation increment at the gangue side was greater than that in the middle of the roadway. In addition, the effect of mining on the cambered side of the roadway was negligible.

### 3.3 | First weighting law of S12013 working face

To describe the characteristics of the first weighting law in the gob-side entry reuse stage, we selected six hydraulic supports at different positions in the working face as monitoring objectives. Figures 11-13 show the curves of the working resistance of the hydraulic support vs. time, and the data used were obtained from the monitoring station. Furthermore, the figures show that the supporting pressure on the hydraulic support fluctuated as time progressed and the working face advanced. The step length of the first weighting was 81 m at the entry retaining side, whereas it was 70 and 4 m in the middle of the working face and at the non-roof-cutting side, respectively. This implies that the crack expansion coefficient at the entry retaining side was higher than the coefficients at the middle of the working face and the non-roof-cutting side.

Furthermore, the maximum and average pressures in different positions represent the zoning characteristics based on the position of the hydraulic support in the working face. The maximum and average pressures at the entry retaining side were 45.2 and 21.97 MPa, respectively. However, in the middle of the working face, the values obtained from the observation station were 46.8 and 22.55 MPa, respectively. At the non-roof-cutting side, the maximum and average pressure were 37.4 and 20.48 MPa, respectively. Therefore, the hydraulic support working resistance in the middle of the working face and the automatically formed roadway side were higher than those in the non-roof-cutting side area. This suggests that the mine behavior in the automatically formed roadway side is stronger than that in the non-roof-cutting side of the working face.

### 3.4 | Periodic weighting law of S12013 working face

The periodic weighting law is often regarded as one of the most important issues to be investigated in coal resource mining, and it is crucial for the design of supporting schemes and safety mining. We obtained an array of pressure data from a hydraulic support monitoring station for analysis. Figures 14-16 provide some of the main characteristics of the hydraulic support working resistance at different positions and times. As shown in the figures, the working resistance of the hydraulic support exhibited evident fluctuations when the working face was used. This enabled the periodic weighting laws for different positions to be determined easily.

At the automatically formed roadway side, the periodic weighting step was 13.30-20.00 m, based on the obtained
However, the numerical values for the middle of the working face and the non-roof-cutting side were 9.40–11.90 and 9.70–10.30 m, respectively. The average values for the three aforementioned positions were 16.70, 10.95, and 9.94 m, respectively. This indicates that the periodic weighting step on the automatically formed roadway side was higher than that in the middle of the working face and the non-roof-cutting side. Furthermore, the average value at the middle of the working face was higher than that at the non-roof-cutting side.

Within the monitoring range, the maximum and average pressures in the automatically formed roadway side were 43.80 and 28.00 MPa, respectively. Accordingly, the values in the middle of the working face were 48.00 and 26.45 MPa. Compared with the values for the automatically formed roadway side and middle of the working face, that is, 30.60 and 21.35 MPa, respectively, the values obtained in the non-roof-cutting side area were relatively small. This indicates that the hydraulic support pressure values at the automatically formed roadway side and in the middle of the working face are higher.
than those at the non-roof-cutting side, similar to the law for the first weighting stage.

4  |  DISCUSSION

4.1  |  Research content

As one of the latest advances in the coal industry in China, the N00 longwall mining method is currently being studied. Recently, methods pertaining to equipment matching, roadway layout, and roadway support have been investigated extensively. Furthermore, the mine pressure behavior law in the roadway retaining stage has been investigated based on field tests, and meaningful results have been obtained. However, studies on the mine pressure behavior characteristics in the reuse stage of roadways formed automatically using the N00 longwall mining method are insufficient. Using field test data in the reuse stage, the primary aims of this study were to analyze the stability of an automatically formed roadway based on the anchor cable force and roof-to-floor deformation, and to investigate the mechanical characteristics of the working face based on the hydraulic support pressure. This study provides insights into the validation of mining space stability as well as addresses the dearth of relevant research.

4.2  |  Stability of automatically formed roadway in reuse stage

Based on an analysis of the anchor cable force and roof-to-floor deformation in the reuse stage of an automatically formed roadway, it appeared that the monitored roadway was balanced by the mining of the working face. This was likely enabled by the roadway support design. Nevertheless, the force increment of the anchor cable in the middle of the roadway was higher than that at the solid cambered side. This might be because the basic roof reinforced by the anchor cable was still undergoing slow deformation as the uncompacted gangue was used to support the roof in the gob. The result of the roof-to-floor deformation, shown in Figure 9, might indirectly support the aforementioned assumption.

Furthermore, the automatically formed roadway in front of the working face in the reuse stage can be classified into three deformation zones based on the severity of the mine pressure behavior: large, intermediate, and creep. The range for the large deformation zone was 0-60 m in front of the working face. Based on field observations, intense rib-spalling occurred at the solid cambered wall of the roadway. This might be because the roof of the roadway...
was perturbed significantly by the movement of the adjacent goaf roof and tended to propagate with the adjacent goaf roof. The intermediate deformation zone was located 60-90 m in front of the working face, based on the obtained data.

The deformation of the roadway was significant and was characterized by a substantial deformation on the gangue side, as shown in Figure 10. When the distance from the working face exceeded 90 m, the deformation occurred in the creep deformation zone. In this area, the roof of the roadway was not affected by mining and remained stable. The foregoing analysis shows that the area up to 90 m in front of the working face was significantly affected by mining. In this area, reinforced support should be adopted to prevent significant deformation and dynamic pressures. In this study, the gangue side was supported using the previously mentioned gangue support technology, which included gangue supports, slidable U-steel bolts at a distance of 600 mm, and a wire mesh. Meanwhile, the solid coal side, namely the arc-shaped wall side, was supported with the gangue support. The distance between adjacent gangue supports was 600 mm on both sides of the automatically formed roadway.

4.3 Mechanical characteristics of test working face

The results obtained in this study suggest that the mine pressure behavior at the entry retaining side is stronger than that at the non-roof-cutting side during reuse, regardless of the first weighting stage or the periodic weighting stage. Meanwhile, the mine pressure at the side of the roadway retention is more severe than that at the side of the roof cutting. The ratios of the first and periodic weighting steps between the entry retaining side and non-roof-cutting side were 20.25 and 1.94, respectively. However, the ratios of the ground pressure strengths at both sides were 1.07 and 1.31, respectively.

To explain this phenomenon more scientifically, the roof structure at different positions was drawn based on masonry beam theory, as shown in Figure 17. Figure 17A, B shows that the roof structures of the conventional longwall mining and N00 longwall mining methods are different. The rock block of the large structure of the overlying rock mass between adjacent goafs was not connected to any element when the conventional wall mining method was adopted. Hence, the mine pressure behaviors on the two sides of the working face were relatively consistent. However, the adjacent goafs
were connected and interacted with each other under the N00 longwall mining method when the working face was mined, resulting in unbalanced mine pressures on the two sides. The rock block is generally unsteady, according to many scholars.

At the entry-retaining side, unstable rock blocks B₁, B₂, and B₃ were formed during mining in the upper segment, namely, the S12012 working face. These three types of rock blocks significantly affected the mining pressure of the working face. Block B₁ revolved and descended to the goaf owing to the moment of force when the working face was mined near the block. Rock block B₁ lost its stability when the working face was mined completely beyond the block. In the aforementioned process, an abutment pressure concentration occurred on rock block B₂, which resulted in high mine pressures on the roadway and working face under this rock block. Hence, the specific features associated with the significant deformation of the roadway and the high pressure of the hydraulic support were observed. Correspondingly, the movement of block B₂ affected Block B₃, but its scope was relatively limited. The foregoing analysis could facilitate the understanding of high pressure on the hydraulic support at the entry-retaining side as well as explain the increase in the deformation of the surrounding rock with the distance from the working face.

Compared with that on the entry-retaining side, the structure of the overlying rock mass on the non-roof-cutting side was more similar to that observed when using the conventional longwall mining method. The block formed gradually and was supported by stable blocks A and C. Stress was concentrated in block A rather than in block B, unlike the case at the automatically formed roadway side. Therefore, at the non-roof-cutting side, the roadway and working face under block B were protected by the block, resulting in a milder mine pressure behavior compared with that at the entry-retaining side.

In addition, in both the first and periodic weighting stages, the pressure step at the entry-retaining side was larger than that at the non-roof-cutting side, primarily owing to the intensified effect of the crack expansion of fractured rocks resulting from the use of roof-cutting and pressure-relief technology. Although the increased pressure step due to the intensification of the roof-cutting and pressure-relief technology is a common scenario, it is supported by only the limited field data obtained owing to difficulties in data acquisition. Hence, further investigations are necessary.

Compared with the mutually independent “O-X”-type failure of the main roof between the adjacent working faces in the conventional longwall mining method, the failure type of the basic roof when using the N00 longwall mining method was significantly different. As shown in Figure 17B, the fracture mode of the old roof underwent a standard “O-X”-type failure when mining was performed in the S12012 working face. Meanwhile, in the second working face, that is, the S12013 working face, the fracture patterns of the basic roof exhibited the “O-Y”-type failure, which resulted in different pressure behaviors at the two ends of the working face. Furthermore, the failure mode of the basic roof above the adjacent working face exhibited the compound patterns of “O-X” and “O-Y,” which induced complicated stress states on the working face during the reuse stage.

5 CONCLUSIONS

The development of the N00 longwall mining method remains in its initial stage. Studies on the evolution law of ground pressure in the roadway reuse state are limited. Herein, we reported the mine pressure behavior characteristics during the reuse stage of a roadway formed automatically when using the N00 longwall mining method, based on a field test at the S12013 working face of the Ningtiaota coal mine. The main conclusions drawn from this study are as follows:

1. The automatically formed roadway can be classified into three deformation zones based on the degree of severity (large, intermediate, and creep), which is affected by mining during reuse. The zone that required intensive reinforcement was located 0-90 m in front of the working face, based on the monitoring results.

2. The mine pressure strength at the entry-retaining side was higher than those at the middle of the working face and non-roof-cutting sides in the reuse stage, based on the working resistance of the hydraulic support. However, compared with the data obtained from the middle of the working face and non-roof-cutting sides, the pressure step of the entry-retaining side was relatively large. Compound “O-X” and “O-Y” patterns for the main roof between the adjacent working faces might have contributed to the aforementioned phenomenon.

3. The results of the investigation indicate that the roadway and working face exhibited satisfactory stability under reuse conditions and that the support design fulfilled the requirements. This study provides more knowledge regarding the N00 longwall mining method and serves as a reference for tackling similar geological conditions when using the abovementioned mining method to excavate coal resources. As such, coal resource conservation and mining safety can be improved.

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CONFLICT OF INTEREST
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