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Analysis of a possible root cause and mechanism for Soma mine disaster

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Abstract

A daunting mine disaster took place in 13 May 2014 at Soma and 301 men lost their lives. Brief information about the Eynez coal mine and some of the inherent characteristics of the field in terms of their effects on mining are presented. This paper basically concentrates on the factors that played an important role in the occurrence of this disaster. Progress of mine fire, firefighting, and rescue activities were only given in basics. Mine fire started suddenly without giving any sign at the hearth of the mine. Sudden occurrence of mine fire and start location properties reveal that the root cause of this disaster was probably not directly related to spontaneous heating of coal. Analysis of roof caving mechanism, subsidence profiles, production history, and overall conditions in the mine showed that the mine fire most probably started as a result of a sudden caving above the nearby sealed out old production panels. Upon caving, pressure of the gas present in uncaved voids and unconsolidated goaf must have increased and gas must have overflown through abundant cracks towards the mine. Gas exuding under moderate pressure might possibly be ignited by a non-ex-proof belt conveyor drive motor starting the mine fire.

1. Introduction

This paper presents an assessment of the root causes of the Soma Eynez Karanlıkdere mine disaster, which was one of the most dramatic coal mine accidents ever happened in the world. There is an around 25 m thick coal seam in the Eynez field. The roof strata is rather massive and strong, creating serious caving problems, whereas there is a very soft clay at the floor of the seam. Owing to the thickness of the coal seam, multi-slicing by the Longwall Top Coal Caving (LTCC) production method is used.

The coal and its surrounding strata, especially floor, contain a considerable amount of methane, and the coal is prone to spontaneous combustion [1, 2]. The coal to be produced in the future lies at deeper levels, and it is known to contain, although it has not been quantified properly, a higher amount of methane. However, methane started creating problems in the field for about 7 years. Therefore, the future production areas would surely be more problematic due to higher stress conditions depending on the depth and methane content. Moreover, the spontaneous combustion liability of coal would certainly make the production more complicated.

This paper presents the technical and site specific reasons behind the disaster. It was aimed at describing briefly the root causes of the disaster. The conditions, crisis management, and rescue works carried out after the disaster are out of the scope of this work. The objective of this paper is not to criminate the people and organizations either. The main objective is to clearly evaluate the technical and geological reasons playing an important role in the disaster mechanism for the purpose of taking the necessary precautions for prevention of the possible future disasters. It is clear that the Eynez field has specific conditions that have to be taken into account during the design and exploitation stages for maintaining a trouble-free production operation. Unless a detailed research program has been put into action

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for an extensive and rigorous determination of all the site specific technical details, it will not be a surprise to realize similar disasters in the future.
There are three underground mines at the Eynez field. One of them just started production in April 2015. Another privately-owned mine is under development at deeper levels located at SW of the field.
The Eynez Karanlıkdere mine, where the May 13th 2014 disaster happened, was first developed by Turkish Coal Enterprises (TKI). The mine and its designated production area was given to Park Technique Inc. (Park) for a period of 15 years, having a minimum production amount of 1.5 Mt/year by means of a service procurement agreement in 2007. The total run of mine production was to be bought with a pre-determined price by TKI. Upon having mainly fire problems in the mine, Park transferred its production right to Soma Coal in 2009. The Eynez Karanlıkdere mine has been operated by Soma Coal since then.
The author of this paper has worked in the Eynez field as an underground production engineer for 4 years, and after joining the university, has kept working in the field for the last 22 years.

2. General information on Soma Eynez coal field

Soma town is located in the western side of Anatolia in the Manisa Province (Figure 1). Soma is 130 km away from the coastal city of İzmir.

Figure 1. Location of Eynez Karanlıkdere underground mine.

In terms of tonnage and quality, Soma Coal Basin is one of the most important lignite resources in Turkey. The Eynez field is the main part of Soma basin [3-5]. The coal resource in the Eynez field in Turkish Coal Enterprises' license area is around 426 Mt. In spite of having records of a limited amount of coal production dating back to 150 years, a systematic coal production has been continuing at the Soma basin since 1939. The open-pit mining method has been mainly applied. Small amounts of coal have been produced in the Eynez field for many years, whereas the production figure from underground has steadily increased up to 9 Mt/year within the last 9 years.

The main coal seam KM2 is of Miocene age and has a thickness of around 25 m. In general, seam dips from NE to SW. The slope of the seam is decreased towards south from 25 to 7 degrees. The seam slope is approximately 12 degrees around the production area of the Eynez mine.

The generalized stratigraphic column at the Eynez field is presented in Figure 2. There are different lithological formations including coal seams. The formations above the Karanlıkdere mine are listed from top to bottom as follow:

- Pliocene age sandstone-siltstone-clay intercalations (P1)
- Middle lignite horizon (KM3, not produced by underground mining)
- Limestone (M3)
- Marl (M2)
- Bottom lignite horizon (KM2, main seam produced)
- Clay (M1)
- Base rock: Crystalline limestone-greywacke

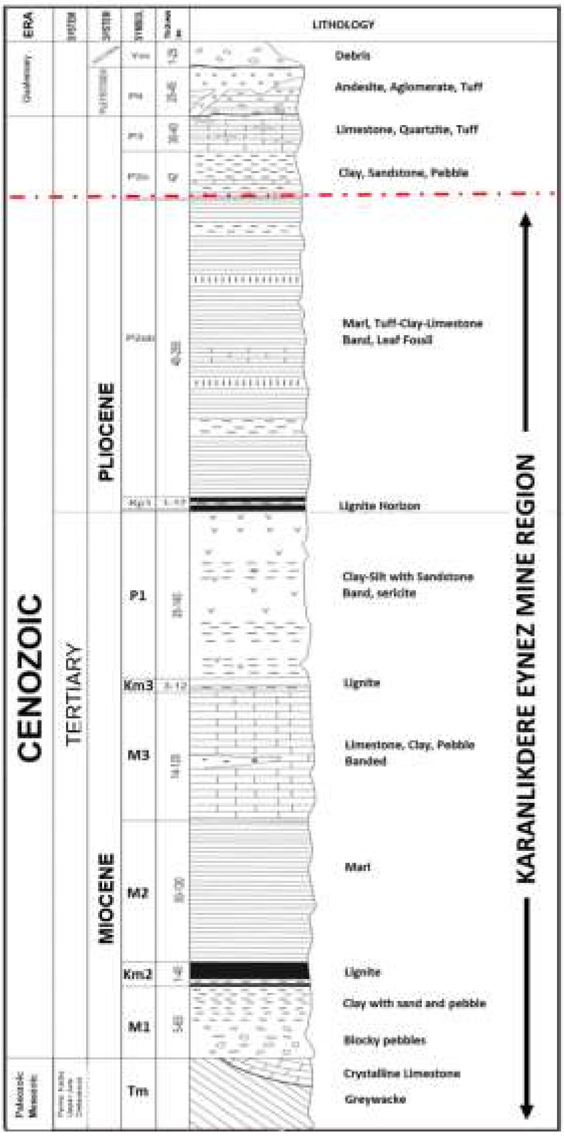


Figure 2. Generalized stratigraphic column of Eynez field.

3. Properties of Eynez coal resource

Coal seam is separated into blocks due to faults. The plan and isometric views of its 3D model is presented in Figure 3. It can clearly be seen in this figure that there are many faults, and consequently, the coal resource is separated into blocks. In these blocks, it has been estimated that 426 million tons of coal resource are present in the TKI license area. The average lower calorific value (LCV) and the ash and moisture contents have been estimated to be 3187 kCal/kg, 34%, and 14%, respectively [5].

Coal seam extends towards SW at deeper levels, where another privately-owned mine is under development. The coal resource in this license area is said to be around 200 Mt.

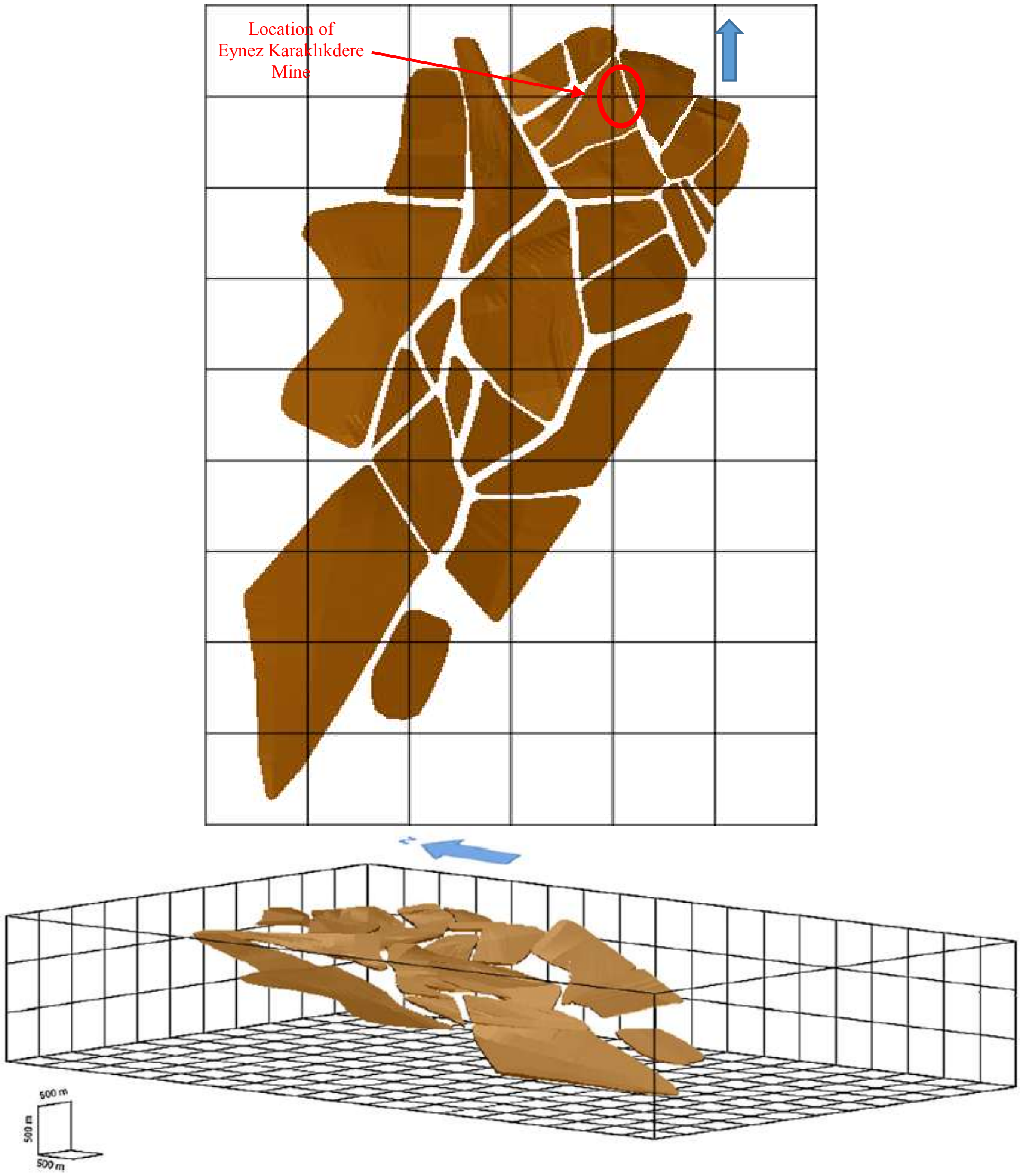


Figure 3. Plan and isometric views of the coal blocks separated by faults in Eynez field [4, 5].

4. Production method

Thickness of the coal seam at the Eynez Karanlıkdere mine is in the range of 18-30 m. The coal quality and mechanical properties change to a great extent from top to bottom of the seam. Its quality gradually decreases from top to bottom of the seam. Additionally, strength of coal at the top of seam is relatively high; as the clay content increases towards the bottom, the coal seam becomes weaker.

The Soma Eynez coal seam is produced by constituting slices at different elevations. Seam inclination in the upper parts (NE) is suitable for the application of horizontally sliced production method [6]. The seam inclination in both the presently produced and future production areas are low enough for conventional longwall mining with intermittent slicing parallel to seam inclination.

Depending on the mechanization level used, three varieties of the LTCC production method are used, namely manual, semi-mechanized, and mechanized. Figure 4 shows the production method generally applied. Although the production method applied is almost the same in principle for the manual, semi-mechanized, and mechanized LTCC, dimensions may change to a certain extent such as extracted seam height and thickness of top coal together with face inclination and direction of advance.

Roof strata of the seam is strong marl, whereas the footwall formation is clay with a very low strength, and its mechanical behaviour is considerably affected by water. Therefore, the first slice (face) is located at the roof contact and the subsequent slices are operated towards the floor. The number of slices may increase up to 4 depending on the seam thickness. To minimize the problems generated from low load-bearing capacity and high plasticity of floor clay M1, the last slice at the bottom of the seam is located by leaving around 1 m thick clayey coal at the floor as a pillar.

A new production strategy has been put forward and opened to discussion for the Eynez field, where the bottom clay hinders problems in production at the lowest slice [7].

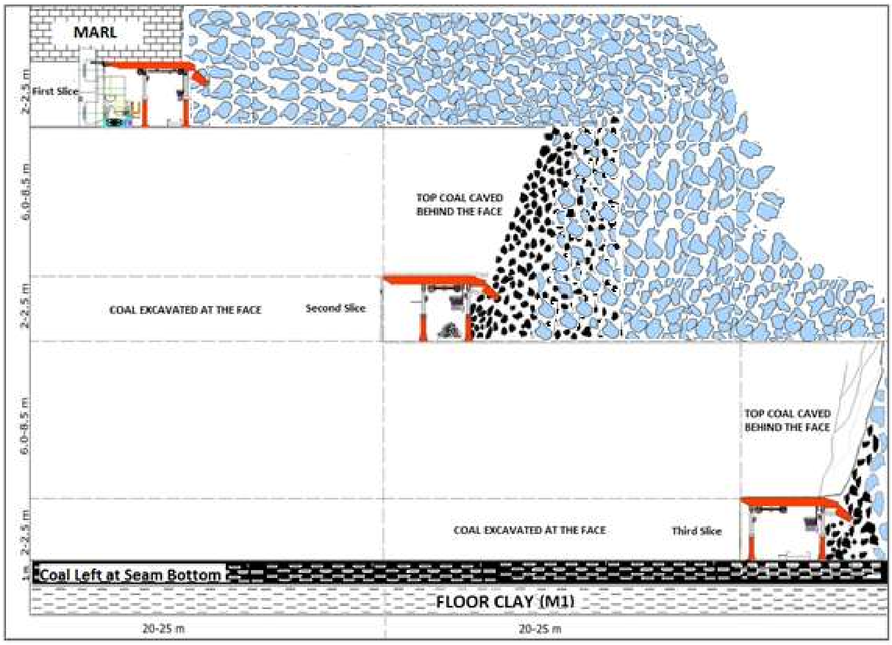


Figure 4. Cross-sectional view of LTCC production method applied at Eynez field (modified from [8]).

4.1. Manual LTCC method

Manual production is a labour intensive method. The face is supported by individual frictional or hydraulic props and corrugated steel roof bars. Timber lagging is applied on roof bars. Coal extraction from face is carried out by drilling & blasting and pneumatic pick hammers. The manual production method is applied where fully and semi-mechanized methods could not possibly be used due to the presence of geological and tectonically disturbed areas. Depending on the seam thickness, coal is produced by means of two or three slices.

4.2. Semi-mechanized LTCC method

The main difference between the manual and semi-mechanized methods is the use of light hydraulic shield supports installed at the face.

Coal excavation at the face is again performed by means of the drilling and blasting method together with pneumatic pick hammers. Due to the safe working slope limitation of light shield support units, the semi-mechanized faces are kept as horizontal as possible. Therefore, around 2.5 m thick coal has to be left at the floor of the face at the dipping side. Although some coal triangular in shape, created due to the difference between the seam slope and the horizontal face, is lost at the bottom, this coal is of low quality due to a high clay content. Somehow, a buffer is formed between the face and the M1 clay layer at the bottom, increasing the face stability condition.

The semi-mechanized faces have better working conditions and also are safer than the manual faces. Nevertheless, the semi-mechanized faces still require a high amount of manpower, and thus the number of workers at the face is almost as high as in the manual faces.

4.3. Mechanized LTCC method

A fully mechanized longwall face is equipped with shield supports, drum shearer, and armoured face conveyor. Fully mechanized faces have safer and wider working spaces than the manual and semi-mechanized ones. Blasting is not necessary for hard coals because coal is excavated by the shearer. The main and tail gates are driven horizontally, as in the semi-mechanized faces. Low quality coal with a high clay content is also left at the floor, similar to the semi-mechanized faces.

5. Factors affecting production and safety in Eynez field

Coal production has been carried out in the Eynez field by surface and underground mines for many years. The characteristics of roof strata, coal seam, and floor clay have been understood to a certain extent over years. However, there are lots of missing technical information that greatly affect the mining operations. Hence, the reasons and mechanism of the Eynez Karanlıkdere mine accident were very much interrelated with these technical details.

Coal seam is classified as a thick seam in the Eynez field. Although this may increase the number of possible production methods, it also makes the production activities more complex in comparison with the thin seam production approaches. Therefore, in addition to an efficient production strategy, selecting the least risky production method is a must. Some important topics must be taken into consideration during the underground mine planning and design stage. The fundamental parameters that should be noted during planning of an underground mine and choosing a proper production method in the Eynez field are listed as follow [5-7, 9-12]:

- Seam characteristics such as thickness, strength, caveability, flowing properties during top coal caving, dip of seam, etc.
- Structure and properties of roof such as strength, caveability, characteristics after caving and compaction, permeability, etc.
- Spontaneous combustion risk and prevention and combatting mine fires,
- Characteristics of floor clay and rate of deterioration in its mechanical behavior in the case of water presence,
- Methane content of coal and its surrounding rocks,
- Amount and rate of production,
- Coal left in the caved area during top coal caving and dilution of run of mine coal,
- Locations and design of main development roadways,
- Rib and protective pillar design.

5.1. Effects of seam thickness and seam attributes

3D wireframe and block models of the entire area have been performed. According to the solid model attributes, the coal seam thickness in the field varies in the range of 1.8-62 m [5]. Variation characteristics of the coal seam thickness is certainly an important factor affecting the production method and strategy selection.

Production in the field has been basically carried out via horizontal slices and top coal caving. In a mechanized longwall, coal is excavated at the face by a shearer, whereas it is excavated by drilling and blasting in conventional mining. In the top coal caving method, the most critical phase is caving the top coal behind the face and winning of top coal by drawing from the goaf side [9, 10]. In other words, extracting the coal at the face is not a major problem. Application of the method in an efficient and safe manner mostly depends on caving the top coal behind the face. Cutting the face is generally completed in a few hours, and the rest of the time is spent on extracting the caved coal behind the face and preparing the longwall for another face cutting [6]. During the top coal production, the roof rock gets mixed with the caved coal, diluting it, and also a significant amount of coal is left behind the face unextracted. Due to the nature of the work done, there cannot be any method that could completely prevent both of these problems. However, it is also necessary to minimize both the roof rock mixing in the coal drawn from roof and the coal left in the caved area.

Efficiency of extracting the caved coal behind the face may be increased by ensuring a steady flow of the top coal. This can be done by having the top coal in a homogenous particle size distribution as much as possible

[13-15]. Owing to having layers with different caving characteristics, the caving resistant parts of top coal must be weakened prior to caving to maintain an efficient coal production by top coal caving. As the coal seam is made of different layers having various strength characteristics, it is essential to apply the conditioning method to have an easy caving and flowing to the top coal. When the coal seam structure in the Eynez field is investigated, it can be observed that the coal quality decreases from top to bottom, while the ash content increases. With increase in the amount of ash content, the strength decreases. Having a coal seam with varying strength affects the caving properties of top coal in a most significant manner. Also, occasionally, there is a flint stone band with a high strength close to the top sections of the coal seam. In short, it is necessary to artificially weaken (loosening, blasting, etc.) the parts that make caving difficult before top coal caving to ensure top coal flows easily and without problems. Through that process, the production rate and efficiency would increase significantly. The caving mechanism for top coal and the details about the recommended application can be found in the literature [10, 13-15].

5.2. Structure and caving mechanism of roof strata

There is M2 marl, and over that, M3 limestone as the roof strata over KM2 coal seam at the Eynez field. Thickness of M2 marl is around 80 m in the Eynez field. M3 limestone located over M2 marl has a thickness around 90 m. Both the M2 marl and M3 limestone strata are thickly-bedded, having a strong structure. Both strata create significant problems during the caving process. As a result, during the top coal caving, massive, strong, and more or less brittle characteristics of M2 and M3 strata lead to serious caving problems. Examples of the caving mechanism of main roof, formation of uncaved voids in the caved region, and characteristics of subsidence have been well-presented in the literature [16-19]. Subsidence on the surface after production are observed at significantly low rates in comparison with the other mines around the world. Actual time-dependent subsidence measurements have been performed over the D1 and D2 panels at the adjacent Imbat mine, having almost the same structural characteristics with Karanlıkdere mine. The extracted seam height at the D1 and D2 panels were 29 m and 32 m, respectively. The maximum amount of subsidence measured at the field was reported to be 4.6 m at the finishing time of production. The maximum amount of subsidence was measured to be 7.25 m after 750 days after the end of production [20]. Hence, the subsidence factors at the end of production and after 750 days was calculated as 0.15 and 0.23. This is a far small rate in comparison with the rates measured all over the world. Moreover, continuing post-production settlement on the surface indicates time-dependent characteristics of the ongoing caving mechanism at the roof strata.

5.3. Effect of floor clay

There is M1 clay located under the coal seam that reaches significant thicknesses at some locations. Floor clay M1 has a low strength. Its mechanical properties are very much effected by the presence of water. It is common to have water during the production of the last slice close to M1 clay layer. During the production of upper slices, the hydraulic filling method is applied. Therefore, some water percolating through backfilled goaf may still be present in the area in addition to the normal underground water. Therefore, at least 1 m of coal seam over M1 clay contact should be left as a pillar. Otherwise, serious problems would certainly occur during the last slice production at the seam floor. Floor clay is not capable of carrying the weight of mechanized support units due to its plastic behaviour. Different production methods must be studied, especially to increase the production rate. A fully mechanized production in a longwall face located at the seam floor contact has not been applied in the area yet. Therefore, the difficulties in such an application have not yet been experienced. A new production method to maintain application of safe and mechanized production systems has been opened to discussion for the Eynez field [7].

5.4. Effect of methane income

Existence of methane in and around the coal seam is experienced at the deeper parts of the field during the drilling operations. At some panels, at deeper locations of operating mines, a significant amount of methane emission has been observed.

However, the methane content of the thick seam at different elevations and surrounding rocks have not been quantified at the present time. Obviously, the methane content distribution must be determined prior to future production. Just like the calorific value, and ash and moisture content, methane distribution maps along the seam stamp including the surrounding strata should also be obtained. A significant amount of methane income had been determined at the operating mines. Depending on the experience gained from past workings in the field, it is almost impossible to start production without pre-drainage of methane. Thus the methane content of coal must be lowered to safe limits by drainage to reduce the risk. Mine ventilation must also be designed and applied with utmost care because a significant amount of methane income from coal and bedrock is to be expected. Since methane is lighter than air, return airways must be designed in a horizontal or ascending manner.

5.5. Locations and design of main roadways

Under normal circumstances, all the development works including the main galleries are located beneath a coal seam at footwall. Thus the main galleries are not affected by production activities and subsidence. Base rock is a very soft claystone at the Eynez field. Although thickness of M1 clay is thin at the eastern side of the field, it has a considerable thickness at the western side. Therefore, contrary to the generally preferred mining practice, in the Eynez field, it is a must to locate the main roadways above the seam inside the strong M2 marl strata.

Although the main roadways have been opened in a relatively strong M2 marl, they have been supported using a passive supporting strategy. The steel sets and wooden laggings allow loosening of the surrounding rock losing its inherent strength within time. Use of rock bolts and thin layer of shotcrete at places would certainly be a better supporting strategy, in general. Steel sets may be used in conjunction with rock bolts at weaker zones. Therefore, an effective support of the main roadways would certainly decrease deformation leading to a less repair work requirement.

5.6. Spontaneous combustion risk and fire fighting methods

A lot of mine fires have been experienced during the production activities at the Eynez field. It can be confidently claimed that the coal seam has a high risk of spontaneous combustion. Although methane has only become a problem in the recent years due to just starting production at deeper locations, mine fires have always been the major problem in the past. Since the thick coal seam is produced by means of slices and top coal caving, it is inevitable to lose some coal behind the face, which is prone to spontaneous heating within time. Speedy face advance, minimizing the amount of coal left in the caved area behind the face, prevention of ventilation of air circulation in the caved area, inertization of the spontaneous combustion prone atmosphere by filling the voids with fly ash, and/or bottom ash water mixture are the basic mine fire prevention techniques. In general, all of them must be utilized for a safe and mine fire-free operation.

At deeper parts of the seam, the risk of mine fire will be much higher due to the abundant existence of methane. Further precautions must be tightly taken to maintain a safe production. Thus during and after production of each slice, the mined-out area should be filled with power plant ash and water mixture. Besides, the oxygen, methane, and carbon monoxide values should continuously be monitored in the caved area behind the face. Moreover, temperature of the caved area should be monitored for a timely determination of the areas of elevated temperature. Then certain precautions such as inertization with nitrogen, isolation with foams, and hydraulic filling can be applied.

It must be kept in mind that accumulation of firedamp coupled with spontaneous heating in the caved area may lead to explosions. The inevitable existence of voids in the caved area due to adverse caveability characteristics of strong marl and limestone strata, unless special precautions are not taken, would certainly supply the methane, oxygen, and heat requirement for explosions. Controlling the atmosphere in the caved area due to its out-of-reach location would be a critical and difficult task.

6. A brief introduction of Eynez Karanlikdere mine

The underground layout, methods, and conditions of the Karanlıkdere mine are presented for a better understanding of mine fire progress, root causes, and overall mechanism of the disaster.

6.1. Mine layout

The Karanlıkdere mine is connected to the surface at 4 entrances (Figure 5). Three of them are located side by side at NW, where all infrastructures of the mine are located. Two inclines are used as fresh air intake located at the same elevation. The first one was opened by TKI, starting from the +337 level to the +302 level. It is 382 m long. The other incline was opened by the present operator of the mine. It starts again at the +337 level down to +294, having a length of 411 m. As it can be seen in the plan, these two inclines are located parallel to each other. These inclines extent another 606 m to the +152 level, where they are connected to each other. From these points onward, the 448 m long slightly inclined main roadway continues starting from +152 to +142 up to the main junction called the U3 area of the mine.

The third roadway is a level air return way opened at +340 reaching +341 at the end, having a length of 950 m. All of these 3 main developments have a cross-sectional area of 18 m^2 and are supported using TH steel arches and concrete and wooden lagging at different places.

The fourth exit is an old mine air return raise having an inclination of 37^0 serving for 23 years. This air return raise was opened under the supervision of the first author of this paper during his service as an underground engineer at the old Eynez mine for 4 years [21]. At the present time, this incline has no function other than being a fresh air intake way.

The distances to surface from the main junction U3 area by two fresh air intake and exhaust air out points are 1436 m, 1465 m, and 2018 m, respectively. The U3 junction is located at almost in the middle of the mine.

The U3 junction to +341 air return gallery is connected with a single roadway. Starting from U3 junction, the first 206 m is level, and there is a 615 m long incline from +142 to +341 level air return main roadway.

Starting from U3 junction towards the south, air intake and return roadways are located in parallel serving for the A and H panels.

6.2. Production panels

When the mine plan is studied, it can be seen that there are lots of mining activities in a relatively small area. Figure 6 presents the mine structure, in general. Pillars left either to protect roadways or between panels are painted in brown on the plan. When the fact that the main development roadways are opened above the seam, owing to their location, these roadways are prone to any influence created as a result of production activity including stress regime change and caving at lower levels during production. Closely-spaced roadways together with many inevitable connections to access lower levels for the 2nd and 3rd slice faces, the underground infrastructure is rather congested and complicated. This might be attributed to the fact that the mine has never been designed by one company. The mine was designed by TKI at first, having an annual production capacity of 1.5 Mt. Then it was transferred to Park Technique, where new developments were added to the mine. Soma Coal is the third one, and the production amount has reached up to the 3.5 Mt/year level. To reach these production levels, a complicated working strategy using the overall mine licence area had to be simultaneously carried out. Obviously, this must have led to overlook some important details in the mine design and production activities.

S panels are located at the east of this main roadway between the +210 and +280 elevations. There were three faces in operation (S2 manual, S2 semi-mechanized, and S3 semi-mechanized) and one (S1 semi-mechanized) at the development stage.

There are two operating faces at panel A, namely A2 mechanized and A2 semi-mechanized. The production activity was carried out between +95 and +86 levels at panel A. Dip of seam in this area was around 7^0. Production started at Panel A in 2009 by the previous contractor. A coal face was formed at the roof of the seam. For the first time in Eynez, a significant amount of methane emission was observed since elevation of Panel A was the deepest level reached so far. Therefore, production was halted, and Park assigned the mine to the present company, Soma Coal, with the permission of TKI. Then a project was put forward to apply methane drainage in Panel A including opening of a surface borehole, where methane was sucked for drainage purpose (Figure 7).

The deepest production area in the mine was Panel H. Elevation of coal at Panel H was between the +65 and +40 levels. The development work at the panel was started in 2012, and there was only one semi-mechanized production face located at the roof contact. Production at this panel was started in September 2013.

Production at Panel +140 was done by a mechanised longwall face, whereas there was a face that had just started production at Panel R.

Altogether, there were 9 operating longwall faces in the mine at the time of disaster. Worked out panels such as B, C, D, and M, which had a critical role in the mechanism of disaster, can also be seen in Figures 5 and 6.

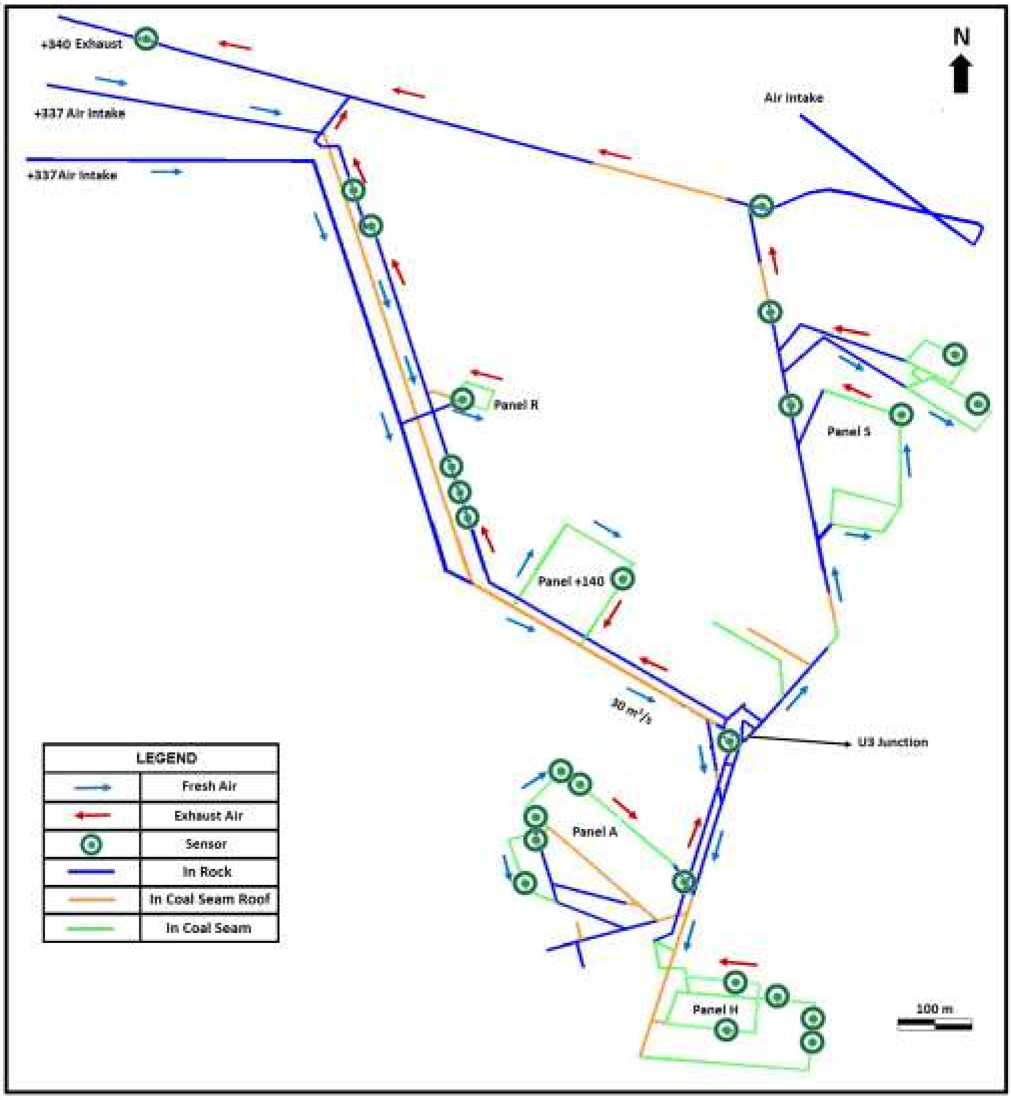


Figure 5. Eynez Karanlıkdere underground mine plan showing locations of operating panels, sensor locations, and ventilation (modified from [8]).

6.3. Mine ventilation

An exhaust fan located at the +340 level sucks the return air out. The other three connections are the fresh air intake points. As it can be seen in Figure 7, exhaust air of the panels A, H, and R are directed to the air return way located parallel to the air intake inclines. However, panel +140 exhaust air was strangely connected to fresh air intake. This air return way is connected to the main air return at the +340 level main roadway. Ventilation of panel S, where there were three operating faces and another one under development, was performed in serial. Exhaust air of faces was fed to other operating faces in the form of serial ventilation. Undoubtedly, this was an awesome way of ventilation. Coal winning at all the faces in panel S were performed by drilling and blasting. Therefore, owing to the fact that production has to be made continuously, breathing of toxic blasting fumes must have been unavoidable at the second or third serially ventilated faces. Witness statements have pointed out the difficult working conditions at panel S. Workers have used the +340 air return gallery to reach the working faces at panel S. No records could be found on the amount of air entering the mine through an old exhaust raise. It is most probable that this old exhaust raise was kept open as it supplied some fresh air to +340 main air return way during the travel of workers employed at panel S.

Although there seem to be two fresh air intake inclines, they certainly function as one as they are connected to a single roadway before reaching the U3 junction. Therefore, practically, the Karanlıkdere mine, having an annual production of 3.5 Mt, had one air intake and one air return way. When the production amount is considered, this certainly is a far too inadequate ventilation system.

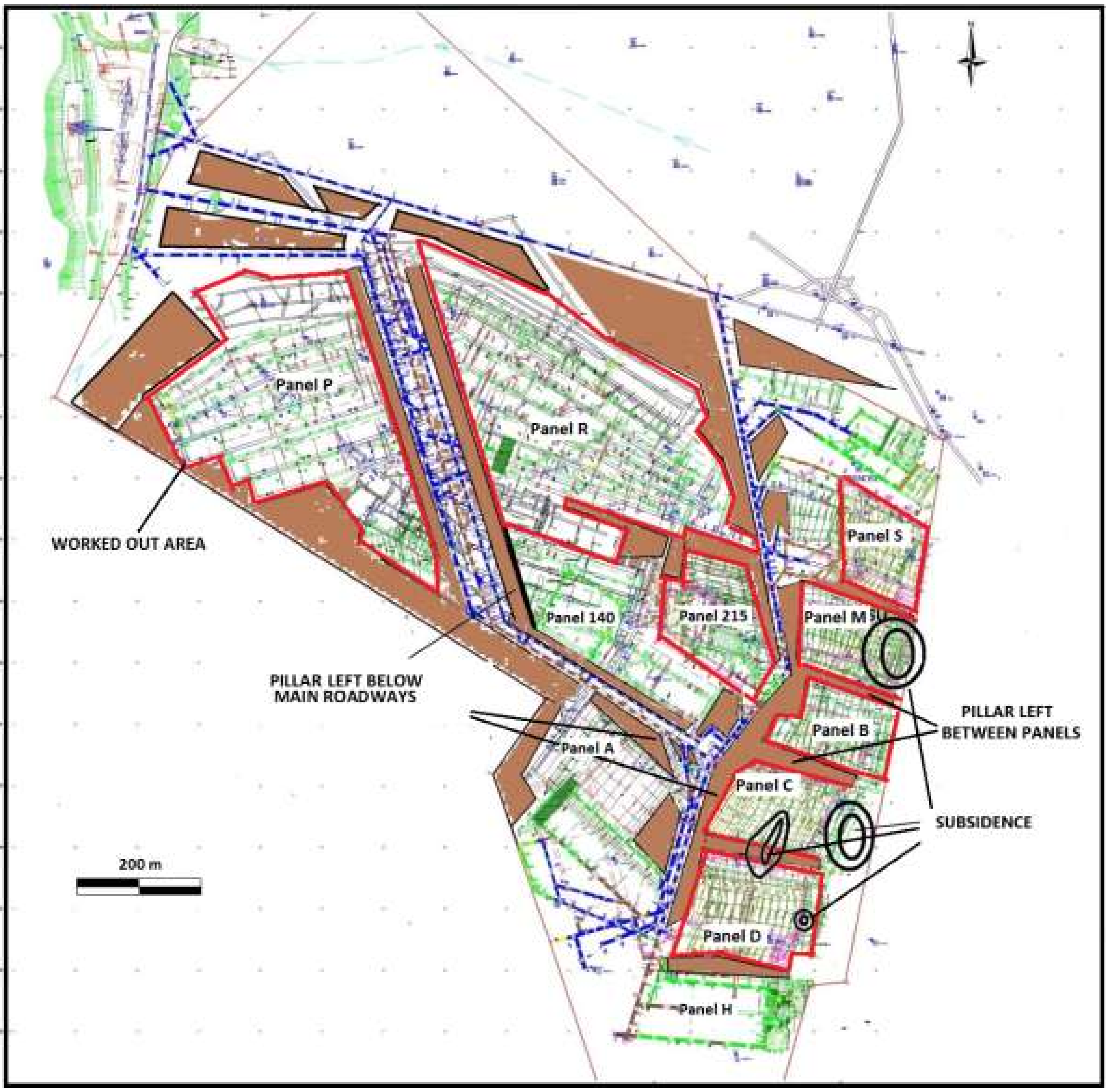


Figure 6. Mine plan showing old and active production areas, protective pillars, and locations of excessive subsidence observed at the surface (modified from [8]).

Figure 7. Methane drainage borehole and facility above Panel A.

6.4. Transportation

As for the transportation system, two fresh air intake inclines were equipped with a coolie car and a belt conveyor system. Materials and personnel transportation were carried out by the coolie car. Some of the belt conveyors were also used for the personnel transportation.

Basically, coal produced at faces were transported to the surface by means of belt conveyors.

6.5. Monitoring system

Sensors were mounted at critical locations of the mine and faces as they could continuously measure the harmful gases inside the mine. There was an underground mine monitoring control room at the surface. There were 27 monitoring stations equipped with 48 independently working fixed sensors. Figure 5 presents the locations of monitoring stations. 19 of these sensors measure methane, 19 of them measure carbon monoxide, 9 measure oxygen, and 1 of them measure carbon dioxide. In addition, there are one pressure and one temperature sensor mounted at the exit of the main return airway.

7. Development of mine fire

7.1. Plan of close proximity of fire start region

A close-up plan of the mine fire start location and structures around are presented in Figure 8. Numbers on the plan are put intentionally for reference purposes in order to explain the area. The roadway at point #1 is connected to fresh air intake. Point #2 is the junction; turning right towards south is the way to panels A and H, and the straight direction is to the U3 junction. The incline having a low slope between point #2 and point #9 was opened for transportation of mechanized face equipment to panel A. Although it was possible to reach the same point by following the way from points #2, #5, and #9, there was a cross-section constraint due to existence of belt conveyor on the way and closure of the roadway due to deformations. The roadway from point #1 towards right was used for an old working in panel A. It was closed and secured by means of a dam, and all the old working area was said to be hydraulic fly ash filled. As clearly seen in the plan, U3 junction was located at the hearth of mine. Roadway from point #5 towards point #11 was the way to panel S, where the most of casualties (272) have taken place. The opening around point #4 was the main transformer station. Roadways shown with point #8 and point #10 were used during production of panels C and D. They were closed; dams were constructed, and the old working area was backfilled with hydraulic fly ash.

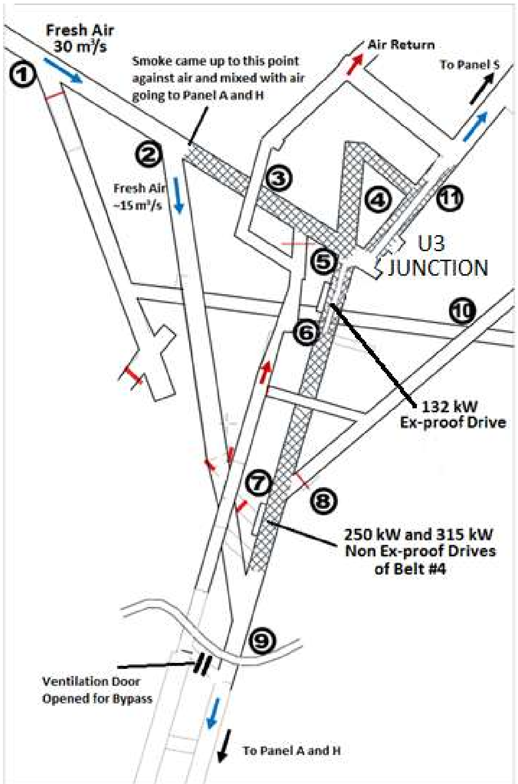


Figure 8. A close-up plan of mine fire start region (modified from [8]).

Fresh air having a quantity of 30 m^3/sec feeding the whole mine comes from point #1 towards point #2. The fresh air was almost halved in two branches; one going towards south for ventilation of the panels A and H and strait towards U3 junction and going towards north for ventilation of panel S. The section between point #5 and point #9 was not well-ventilated, and there was a very slow air flow towards point #9 to point #5. Since this location was not well-ventilated and there were drive motors of the belt conveyor #4, the passage was disturbingly hot, and it was almost never used for a passage way between point #5 and point #9 by the personnel.
There was the belt conveyor number #3 between point #1 and point #5, and the belt conveyor #4 between point #5 and point #9 used for coal haulage.

7.2. Evaluation of witness statements

There were people working close to the mine fire start location. Therefore, their witness statements are the most valuable information in understanding how mine fire has started. Gas monitoring data supplied critical and valuable information, especially for the start of mine fire; however, due to power cut-off and/or exceeding the gas detections limits of sensors, the most critical data could not be obtained for a comprehensive understanding of the mine fire progress within time.
According to witness statements of workers, the smoke was spotted at 14:45 in May 13th, 2014. Since the region where the smoke has been realized is located at the centre of the mine, there were workers in a close proximity of the area. Around point #5, which is the closest point to where the smoke was seen, there were 8 workers. As one of them was the switcher of belt conveyor #4, the others were doing mainly repair work. There were 7 men between point #5 and point #3. There were another 3 workers at point #4 and 4 workers performing support repair work just a little further up to point #1.
It should be noted that witness statements of workers on the conditions encountered on start of mine fire did not have any conflicts. All of the workers claimed that just before they had seen smoke, there was no extraordinary condition present in the vicinity of mine fire start location.
The responsible worker attempted to start the belt conveyor #4 but somehow the belt had difficulty in running, and he turned it off. As he was about to start the belt, again workers at about points #5 and #6 have shouted that they had seen a smoke coming. He switched on the belt again but it did not start. He saw the smoke coming from the point #6 direction and switched the belt off. Within a time of less than one minute, the smoke was all over the place. Then the workers around point #5 walked towards point #2 to fresh air direction. At first, the smoke was of white colour, and within around one minute time, it turned out to a thick black smoke.
As the workers were walking towards point #2, the smoke followed them against the air flow direction. At first, the smoke was at the roof, having a significant turbulence; however, a little later, the smoke covered all of the cross-section of the roadway. Then the smoke started to go into coolie car way from point #2 towards point #9, which was the fresh air intake for panel A and panel H.
An important point that must be noted here is that nobody in the mine has seen an open fire and/or a flame; all that everyone has seen was the white-yellowish smoke at first, then black smoke.
Witness statements undoubtedly reveal that the cause of mine fire cannot be due to spontaneous combustion of coal. As a matter of fact, there is no coal cut in the roadway between point #5 and point #9. During our visit to mine with the members of parliament, we were able to see the mine fire start location.
First, smoke was seen in the mine around 14:45. At around 17:45, the direction of ventilation was reversed. Two days later, air direction was once more changed to the original condition. As reversing the direction of ventilation is always a critical application in mining, effects and consequences of this application at Karanlıkdere mine disaster was not evaluated in this work. The main concern of this work was the assessment of root causes of the disaster. However, progress of mine fire, firefighting efforts, crisis management, and rescue operation must be further analyzed together with the consequences of reversing ventilation direction.

7.3. Evaluation of monitoring data right after start of mine fire

There were 27 monitoring stations having a total number 19 CH_4 and again 19 CO sensors (Figure 5). There were 9 oxygen and 1 CO_2 sensors in the mine. All of the engineers and technicians were known to carry portable gas measuring equipment capable of measuring CO, CH_4, O_2, CO_2, and temperature. The measured data from portable equipment was decoded and present at the court;

however, the authors were unable to get these data.
Table 1 presents gas concentration measurements obtained from monitoring system during the fire start time. The authors could only access these measurements. Unfortunately, it was not possible to obtain and analyze all measurement data.
Figure 9 summarizes the measured CO and CH_4 results. In accordance with the witness statements, just before the fire broke up, there was no abnormality in the readings. Within a very short period of time (7 minutes), CO readings had exceeded 500 ppm of detection limit of the sensors. This phenomenon surely indicates that fire has broken up suddenly. Undoubtedly, how fast a spontaneous combustion has taken place, there would have been no way that temperature would reach up to the ignition point; burning belts, cables, timber, coal, and whatever has got a burning capability within 7 minutes. Therefore, the reason for the mine fire cannot be due to spontaneous heating of coal. As a matter of fact, the place where fire broke up has no coal surrounding the roadway; the roadway was completely in marl formation.
Sensor #405 measured a CH_4 concentration of 3.94% at 15:14. Although it cannot be confidently claimed that this measurement is correct due to a probable fault in the sensor, it can still be a very important indication related to the root cause of the disaster.

Table 1. Some gas measurement results obtained from stationary sensors [8].

Time	Sensors				
	#545 CO (ppm)	#501 CO (ppm)	#431 CO (ppm)	#471 CO (ppm)	#405 CH_4 (%)
14:48	-	-	-	-	0.201
14:49	-	-	-	-	0.201
14:50	-	-	-	-	0.201
14:51	-	-	-	-	x.x
14:52	-	-	-	-	x.x
14:53	-	-	-	-	x.x
14:54	4.973	0	-	-	x.x
14:55	4.973	0	-	-	x.x
14:56	4.973	0	-	-	x.x
14:57	6.969	0	-	-	x.x
14:58	12.957	0	-	-	x.x
14:59	56.871	0	-	-	x.x
15:00	128.729	0	-	-	x.x
15:01	282.427	0	-	-	x.x
15:02	454.090	0	1.961	-	x.x
15:03	500.000	50.980	1.961	-	x.x
15:04	500.000	135.294	25.867	-	x.x
15:05	500.000	249.020	73.678	-	x.x
15:06	-	378.431	169.302	1.961	x.x
15:07	-	500.000	312.737	1.961	x.x
15:08	-	500.000	500	1.961	x.x
15:09	-	500.000	500	1.961	x.x
15:10	-	-	500	1.961	x.x
15:11	-	-	x.x	486.055	x.x
15:12	-	-	x.x	x.x	x.x
15:13	-	-	-	x.x	x.x
15:14	-	-	-	x.x	x.x
15:15	-	-	-	386.447	3.904
15:16	-	-	-	x.x	x.x
15:17	-	-	-	x.x	x.x

- Data not available.
x.x No measurement either due to power cut-off or concentration exceeding detection limit.

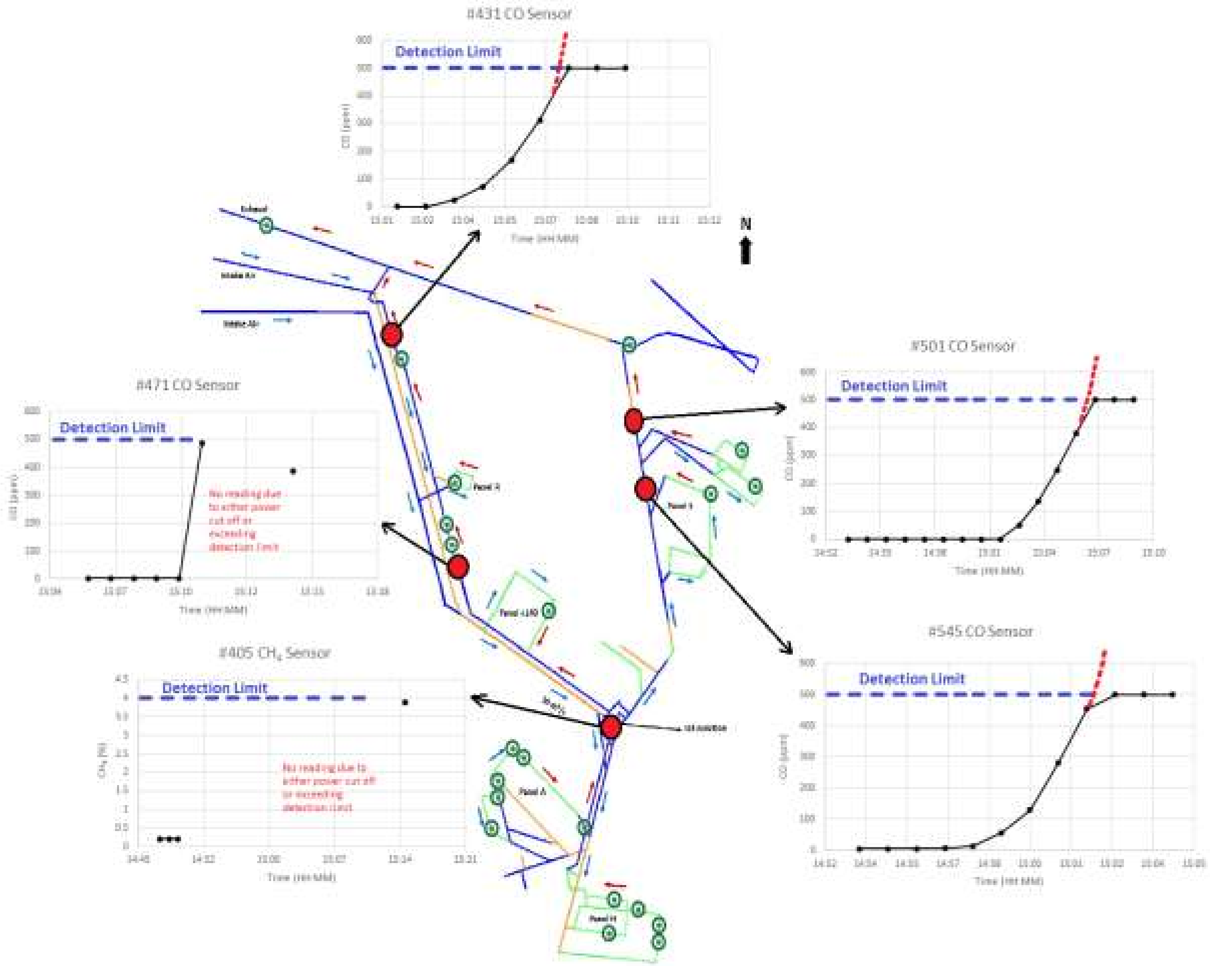


Figure 9. Monitoring data of selected sensors and their locations.

The CO sensor #545 located at tail gate of S-2 conventional face readings changed from 4.973 ppm to 500 ppm, which is the detection limit of the sensor. In 7 minutes between 14:56 and 15:03, these readings continued until the system failure at 15:10. After 15:10, it was not possible to take readings from the CO sensor #545.

Similar to sensor #545, according to sensor #501 located at the main return airway, CO readings increased rapidly. From the readings, it can be said that atmosphere having a high CO content reached sensor #501 after 4 minutes.

There was also a rapid increase at the CH_4 sensor #423, like the CO sensors. Methane reading was 0.059% at 15:03, and after 7 minutes, it increased to 0.358% at 15:10. After 15:10, no reading could be taken. Even though 0.358% of CH_4 value was well under the critical value (1%), the rate of increase could be regarded as significant.

Also methane sensor #426 located at the exit of #340 main return airway readings showed a significant increase in the methane concentration. As shown in Table 1, methane readings were constant until 15:10, and there were no readings between 15:10 and 16:01. From 16:01 to 16:07, there were 6 readings with 0.72% methane.

Gas measurements taken by the Turkish Hard Coal Enterprise's (TTK) rescue team at the exit of main exhaust airway are presented in Table 2. Unfortunately, gas measurements at the surface outlet of the mine started approximately 44 hours after the mine fire had started. CO concentration after 44 hours was around 3000 ppm, and then a gradual decrease could be observed over time. It is a pity not to have timely information on the mine exhaust gas analyses at the surface outlet of the mine. A complete gas analysis carried out at the earlier stages of mine fire could have supplied invaluable information.

Table 2. Gas measurement results at the main exhaust airway portal [8].

Date	Time	CO (ppm)	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)
15.05.2014	10:45	2800-3000	0.2	2.25	18,1	5
	11:45	2430	0,2	2.05	18,4	5
	12:45	1855	0,2	1.84	18,8	3
	13:45	1600	0,2	1.72	18,9	3
	14:45	1405	0,2	1.6	19	3
	15:15	1320	0,2	1.5	18,9	3
	15:45	1305	0,1	1.6	19,4	2
	16:45	1170	0,1	1.5	19,2	3
	17:15	1015	0	1.3	19,1	3
	18:15	874	0,1	1.28	19,5	3
	19:15	758	0,1	1.2	19,2	2
	20:15	704	0,1	1.2	19,2	2
	21:15	658	0,1	1.2	19,2	2
	22:15	554	0	1.1	19,3	2
	23:40	464	0	1.06	19,3	2
16.05.2014	01:10	351	0	1,04	19,3	1
	02:10	301	0	1,02	19,3	1
	03:10	228	0,6	1,4	19,3	1
	04:00	264	0	1	19,3	1
	05:00	240	0	0,98	19,4	1
	06:00	224	0	0,94	19,4	0
	07:00	218	0,7	0,96	19,4	0
	08:15	206	0,1	1	19,3	0
	09:15	178	0	0,86	19,4	0
	10:30	138	0	0,82	19,4	0
	15:50	119	0	0,82	19,5	0
	15:50	111	0,3	0,58	19,9	0
	17:00	108	0,3	0,57	19,9	0
	18:10	96	0,3	0,58	20	0
	19:30	89	0,3	0,58	19,9	0
	20:40	165	0,5	0,46	20	0
	21:40	146	0,4	0,4	20,1	0
	23:20	126	0,4	0,39	20	0

There are two important witness statements to be mentioned here for understanding the mechanism:

- A crew of workers working between points #3 and #5 claim that a boulder size rock has fallen from the roof, touching slightly the shoulder of one of them. They realized that a grey-blackish smoke was coming through the fractures in the rock at the roof from the place where the boulder was fallen. Then smoke from point #5 towards point #3 started to come in an increasing manner.
- During fire fighting efforts after 2 days of fire start, a strong flame at point #1 in front of the dam constructed for isolation of an old production area shown in Figure 8 was observed. The engineers and workers claimed that this was definitely a different flame in comparison with other locations as if a gas coming above the dam thorough cracks was burning. It was also stated that although the fire at other locations could easily be put out, this flame could not be extinguished.

7.4. Change in color of smoke

The color of smoke was white-yellowish at the beginning, and turned into black within minutes. In general, a hotter fire will convert more fuel into elemental carbon, which forms into tiny particles that absorb light and appear in the sky as black smoke. A cooler combustion or one that does not work as efficient yields less pure forms of carbon. These tend to reflect light, making the smoke look white.

The basic by-products of a fire are carbon dioxide and water. You cannot see carbon dioxide but water in the air might make smoke appear lighter in color. Plastic products on fire tend to burn very black because most of the fuel is converted into elemental carbon. There is also very little moisture in plastic products to make the smoke look lighter [22].

Therefore, at the beginning, heat generated in the fire area was low, creating light-coloured smoke. As soon as the heat increased in the area, temperature must have risen, and ignition of plastic products resulted in the change of smoke colour from white to black.

8. Toxicologic analyses of victims' blood samples

The number of casualties at the air exit direction towards S panels from U3 junction were 272. A total number of 15 men lost their lives at panel A and panel H, whereas the casualties were 14 at the air return way located parallel to the main air intake.

Blood samples were taken from 279 victims and analyzed. According to these analyses, the blood carboxyhemoglobin (COHb) values of 279 workers varied between 44.3% and 99.6%; 272 of them had over 60% COHb in their blood samples [8].

The specialist declared in the toxicology report that the CO content of inhaled air must have been over 1000 ppm to have a COHb level of over 60%. It was stated that after mine fire accidents, a COHb level in the blood of any victim had never been measured over 90% before in the world. The COHb levels of victims were found to be 99.6% (body no 267), 95.8% (body no 276), 93.6% (body no 269), and 91.3% (body no 273). To have such an extraordinary COHb level 1 in a victim's blood, the atmosphere must have contained over 10.000 ppm CO concentration. Therefore, this phenomenon also proves that the CO concentration has risen over 10.000 ppm within a time of around 10-15 minutes [8, 23].

9. Results of in situ investigation

The committee including the authors of this paper, experts, and MPs went to the Karanlıkdere mine in October 30th 2014 to officially see the place where the mine fire had started for the first time. Burnt out conveyor belts and wooden laggings used to support roof were seen at many places.

At first, the committee proceeded from point #2 to point # 9 and further down towards the panel H and panel A direction. We have clearly seen that along this coolie car way, there was no sign of burning. Workers claimed that they cut the belt as the fire was approaching towards them. When the tensioned belt was cut, the burning part had thrown further. Therefore, we have observed indications of fire and burning along around 30 m. However, towards point #9, along around 12 m, there was no sign of burning.

A dam was constructed at point #9, limiting access to U3 junction.

The place where the mine fire has started (Figure 8, between points #5 and #7) had special features indicating the starting mechanism of mine fire. Findings at this location were as follow:

- Two main drive motors of #4 belt conveyor was hydraulically filled with fly ash. These motors were said to be non ex-proof. We were not able to see these motors.
- There was no intersection of coal observed along the whole roadway between point #5 and point #7. Fire start location was completely in rock. However, the hydraulic ash filled area could not be seen.
- Belt conveyor #3 head drive region was completely caved between points #5 and #3.
- Between points #5 and #6, TH steel arches were standing; however, there was a large opening formed at panel A side and the roof. The wall of roadway at panel C side was completely crushed.
- Belt #4 first driving the motor region was completely destroyed. There was an opening having a width of 4-5 m and a length of 5-8 m along the roadway. TH steel arches were again standing. There was a fault forming a weak zone at this location extending across the roadway.
- Caved rock from the roof has formed lots of rock heaps at the floor and covered the drive motor.
- At the sidewalls of the roadway, there were empty spaces having a depth of 2 m and length of 5 m.
- Monorail at the roof was completely destroyed.
- By looking at the empty spaces at the roof, we have seen smoke-stained rocks. This is an indication that caving from the roof was stopped when there was fire burning.
- From point #5 towards #11, wooden lagging at the roof was burnt out; however, there was not a clear sign of burning at the side-walls. This is an indication that fire was in the form of a flame at the roof, not at the sides.

The findings presented above were in good agreement with the witness statements of technicians and engineers who were able to pass through this location during firefighting trials. This was about 3 days after the fire starting time.

10. Root cause and mechanism of disaster

Figure 10 presents the mine plan on satellite image, showing the important futures that are of significance importance to understand the root cause and mechanism of the mine fire. It is for sure that by means of witness' statements and sensor readings, everything was as usual in the vicinity of mine fire start location right before the mine fire had started. There is no doubt about the mine fire start location. Experience of smoke was almost instant. At first, the smoke was white-yellow, and then it turned out to be a thick black smoke. Although the passage between point #5 and point #9 where the belt #4 drive head was installed was not frequently used by workers for walking through, both ends were walked by hundreds of workers every shift and the mine fire was started in a roadway opened completely in rock. Therefore, the cause of fire cannot possibly be due to classical spontaneous combustion.

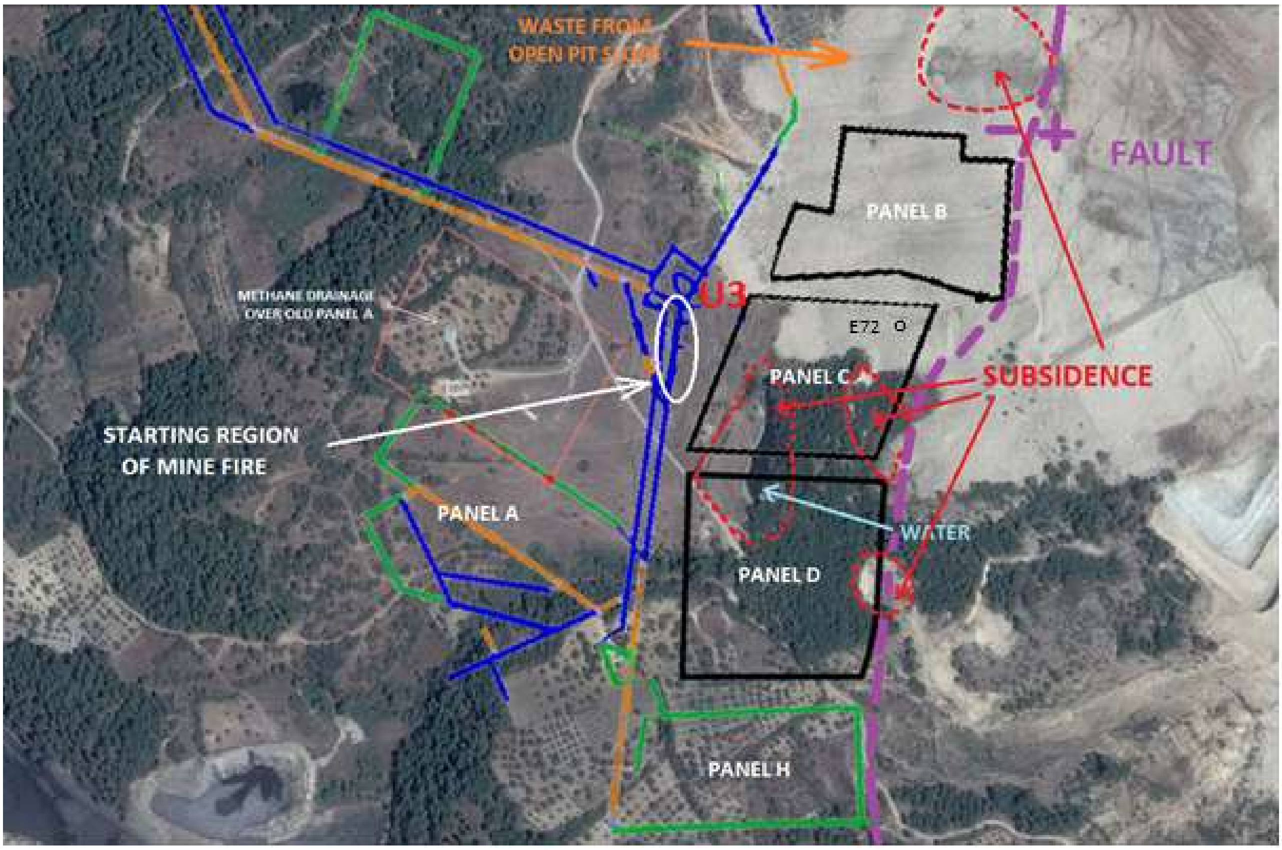


Figure 10. Details of mine plan on satellite image.

10.1. Production activities around mine fire start location

The starting region of the mine fire shown in Figure 10 was surrounded by production panels. Panel A was located at west. Production at panel A was performed at a longwall face located at the coal seam roof contact in 2010. Due to the high methane income, production was stopped, and a borehole at the surface was opened for methane drainage purpose (Figure 7). Just a few days before the disaster, a new mechanized longwall face was started in panel A. Therefore, around panel A, only the top of the coal seam was produced, leaving the rest for future production. The coal seam near the fault zone was produced using the blasting gallery method at panels M, B, C, D, and H. Production at panel B, panel C, and panel D started in March 2010, June 2010, and May 2011, respectively. Upon performing production by means of three slices, these panels were finished and sealed off in March 2012, September 2013, and January 2013, respectively. After finishing production, the panels were said to be filled with hydraulic fly/bottom ash.

During production of panel C and panel D, a relatively high methane income was observed, and the workers and engineers have claimed that production had to be stopped due to high methane concentration, and the working areas were evacuated many times. In addition to the methane problem, engineers working in the mine declared that the roof at panel A, panel C, and panel D were rather strong in comparison with the other panels in the mine and created a lot of problems such as formation of non-caved area at the goaf and sometimes violent caving.

10.2. Subsidence through over adjacent panels and its relation with disaster

As mentioned earlier, there are thick and strong marl (M2) and limestone (M3) strata above the coal seam (Figure 2). Mechanism of subsidence observed at the surface due to underground production in the Eynez region has been rather different in comparison with the subsidence development observed at underground coal mines around the world. Due to the existence of a rather massive and strong marl and limestone strata reaching a total thickness of around 170 m, caving could not occur in a continuous and homogenous manner. Figure 11 presents the log of an exploration borehole opened from surface on panel C. When the core recovery values were considered, it could be seen that core recoveries were 100% at many locations in M2 and M3 formations, proving their intact and strong structure.

Unfortunately, no systematic subsidence measurement had been carried out during production at the Karanlıkdere mine. Only locations of excessive subsidence and sinkhole formations were drawn on plans. These features could even be seen at google earth images, as shown in Figure 10. There is a large sinkhole formation at the surface at panel M and fault contact (Figure 12). Even this area was filled and leveled; indications could still clearly be seen on the surface. There must be a sinkhole formation also over panel B. Although some indications of subsidence at panel B fault contact can be seen on google earth image, it cannot clearly be pointed out due to the waste flowing from open-pit overburden dump area.

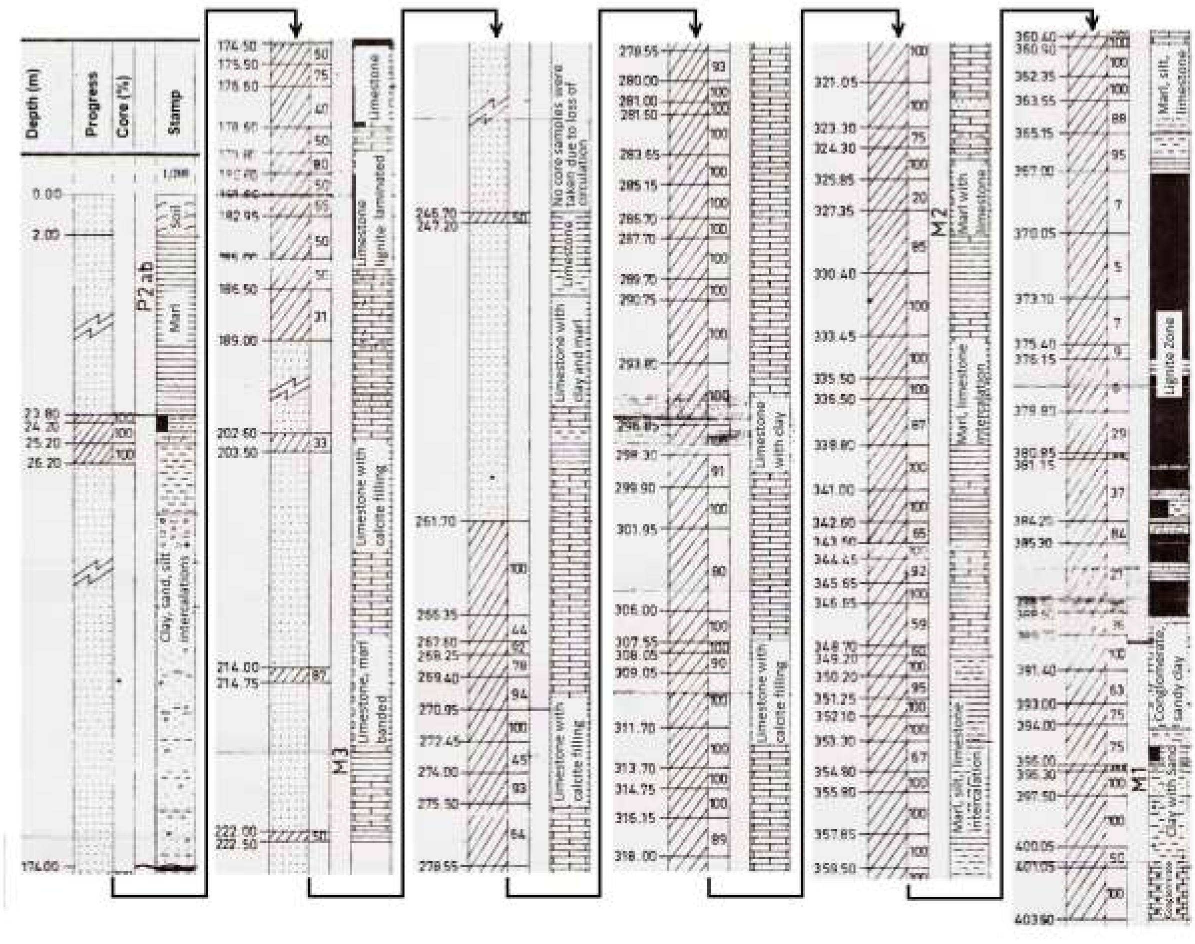


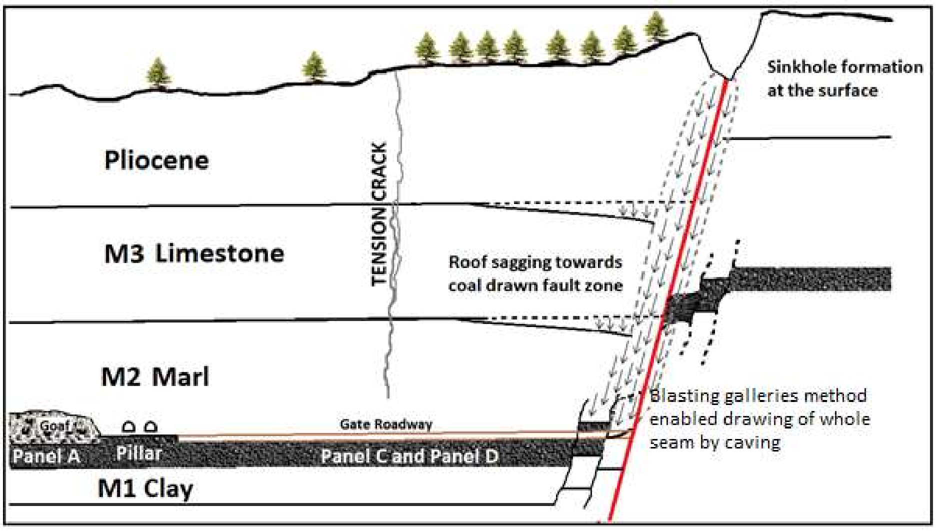
Figure 11. Log of the surface exploration borehole E72 opened on panel C.

Figure 12. Subsidence sinkhole over panel M.

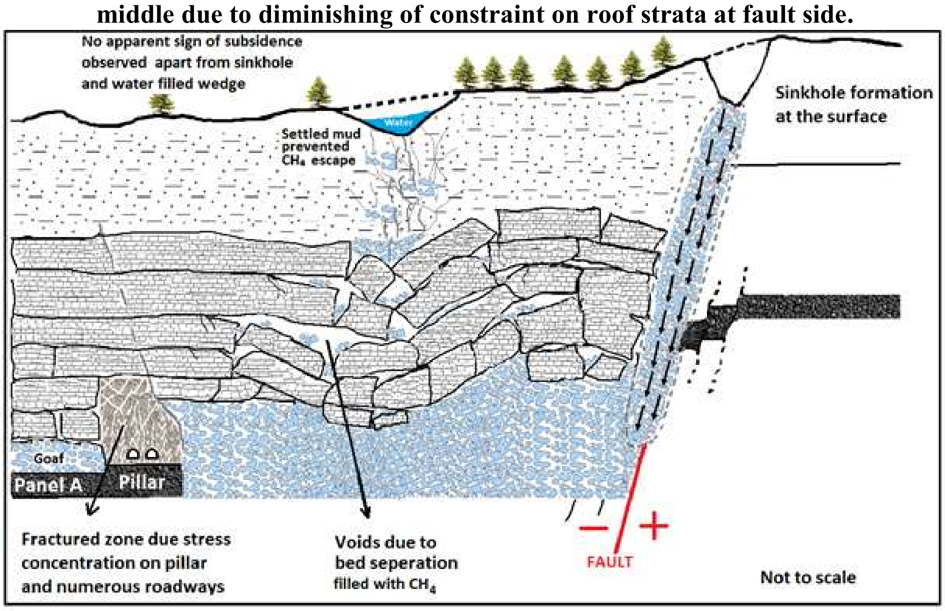
Relationship between the subsidence and sinkhole formations on the surface above panel C and panel D is rather important in understanding the mechanism of roof caving during production at these panels. At the fault contact of both panels, subsidence sinkholes were formed, as shown in Figures 10, 12, and 13.

Mine plans and interview with engineers showed that the coal seam near the fault zone had been thrown up due to the dragging effect of the fault. Figure 14 shows the structure of coal seam and locations of panels schematically. During the top slice development of the coal seam, almost horizontal main gates and tailgates are opened along seam strike at panel C and panel D. Using the blasting gallery method, the entire coal seam was produced by drawing the complete seam height near the fault zone. As the roof strata and coal seam itself were well-disturbed by the fault zone, it was easy to draw the top coal without any major difficulty. However, drawing the complete seam height must have created an unbalanced beam formation on the M2 marl and M3 limestone layer. Around the drawing region, support of the M2 and M3 layers must be lost, forming an unconstrained beam at the fault side. Excessive drawing of coal parallel to fault plane have created huge sinkholes at panel M, panel C, and panel D. Surely, there was a similar sinkhole formation above panel B, where it was covered with sliding debris from waste dumps of open-pit mine. Therefore, the roof layers were clamped at the western side, and the support was lost on the eastern side, i.e. parallel to the fault plane. The beam must be broken at a certain distance parallel to the face and fault plane. Hence, a tension crack must be formed across panel C and panel D. This crack exactly coincides with the water filled wedge observed at the surface (Figure 13). The sinkhole formed over panel D, shown in Figure 13(a), was so deep that although it was filled with 1250 tons of truck load of rock, it was still very deep. Formation of a huge tension crack between panel C and panel D definitely affected the caving mechanism during the production of these panels. As the coal was produced in three slices in these panels, a huge crack formed perpendicular to the advance direction governed the caving. During production, the wedge-like subsidence was created as the wedge must have deepened during the subsequent productions of slices from top to bottom. This phenomenon is schematically shown on a drawing in Figure 14. Water accumulated in the wedge must have filled the possible escape ways of the accumulated methane inside the goaf. Apart from the sinkholes and subsidence along the fault line and the water logged wedge, no signs of further subsidence could be observed at the surface. When it was considered that around 25 m thick coal seam was produced, its indication on the surface was not visible apart from the features described above. This must be due to the strong and massive characteristics of the M2 marl and M3 limestone strata. In addition to this, the M3 limestone strata is known to have natural dissolving caves. It is frequent at the Eynez field not to have circulation during exploration drilling, especially at the limestone layer. Such a zone has also been seen in the surface exploration borehole log presented in Figure 11. Although a 25-m thick coal seam was produced, the maximum amount of subsidence was said to be not more than 8 m. Therefore, it is obvious that judging by the formation of subsidence at the surface, there must be voids in the form of triangles created as a result of bed separation above the production areas. As the goaf was not loaded properly due to bed separation and formation of voids, consolidation of caved rock would not have been effectively taken place. Hence, unconsolidated goaf can have a lot of empty space for light methane to fill in.

Figure 13. a) Sinkhole over panel D fault contact, and b) water filled subsidence wedge formation across panel D and panel C.



a) Formation of sinkhole due to full stamp caving of coal at fault contact and formation of tension crack in the middle due to diminishing of constraint on roof strata at fault side.



b) Caving of roof after production of three slices resulting in void formation filled with methane due to bed separation and unconsolidated goaf.

Figure 14. Schematic illustration of sinkhole, tension crack, and subsequent water filled wedge-like subsidence formation on the surface.

Caving of strong strata would certainly take place in a dynamic manner. Caving above a longwall panel would continue for a long time in a progressive and intermittent manner towards surface. When a considerably large caving takes place, as the basic physics rule would well-explain, volume would decrease, leading to increased gas pressure inside the chamber. Since the surface cracks were completely sealed with precipitating mud, compressed gas in the bed separation caves and unconsolidated goaf would only flow towards the mine in the form of an inrush through the weakest link. Pressure of gas leaking inside the mine would definitely decrease within time, as the case of a punctured tire. Unfortunately, an ignition source during gas leakage inside the mine would easily start fire. Hence the result is well-known in the Karanlıkdere mine.

As stated earlier, during investigation of the fire start location, the disturbed nature of surrounding rock and empty space formations due to caving could clearly be seen supporting the mechanism described above.

Gaseous mixture consisting of mostly methane and CO caught fire between points #5 and #7 near the belt conveyor #4 drive motor. There may be 3 basic reasons for the gas catching fire:

- Belt conveyor #4 drive motor being non-ex-proof and/or,

- Due to spontaneously heated coal at the pillar between panel and the roadway,
- Ignition of dust due to friction of belt conveyor.

However, the second and third reasons seem to be less likely. According to the witnesses' statements, it is most probable that a spark caused by belt conveyor #4 motor, which was said to be non-ex-proof ignited the gas during switching on. Unfortunately, this motor was buried with hydraulic ash filling by the company after the disaster. It was stated by a surviving worker responsible for starting the conveyor belt #4 and some other workers nearby that a white smoke had come at first upon turning on the switch to start the belt. The belt could not start probably due to overloading. It was further expressed by witnesses that in the beginning of the fire, a white yellowish smoke was present but after a few minutes, the smoke turned into pitch black and shut down almost all the visibility.

Ignition of fine coal settled around the belt conveyor might have started the mine fire. However, just before the start of fire, the belt conveyor was not working. An increase in the temperature leading to ignition would certainly yield smell and smoke to a perceivable level as there were workers around the fire start location. It should be kept in mind that according to witness' statements, there was nothing unusual around the fire start region before the event. Nevertheless, this possibility should also be carefully studied.

As a conclusion, the fire at the Eynez mine was possibly originated due to seizing and ignition of mainly methane pressurized after a sudden caving at roof strata over worked-out panels C and D. Pressurized gas must have come to the whole U3 region. The points proving this mechanism can be listed as follow:

- Absence of coal around fire start location,
- No reports of any change in the vicinity of fire start location until a few minutes left to the inception of fire,
- Raise in CO concentration level within a couple of minutes,
- Well-known poor caving characteristics of roof strata. Subsidence observed at the surface, clearly indicating the formation of voids due to bed separation above panels C and D,
- A significant presence of a water pool across panels C and D, forming an effective seal eventually preventing the escape of methane to the surface,
- Relatively high methane income during production of panels C and D,
- Repulse of smoke to the air income direction and even reaching point #2, proving existence of fire in high power. This can only be supplied by burning a considerable amount of gas,
- Significant amount of caving at the roof and walls around the mine fire start location showing gaseous mixture income under moderate pressure,
- Torch-like flame presence in front of the old working dam at point #1 during fire extinguishing. This is an indication of methane income through cracks at the roof,
- Reading of 3.9% methane level that could be an indication of methane inflow at the return airway after 25 minutes of fire start,
- Witness statement of smoke coming through the fractures at the roof, indicating increase in gas pressure at the roof,
- Clear indication of burning timber at the roof, only indicating a flame made up burning of a lighter gas such as methane.

10.3. Results of observation at adjacent mine

Production was started at the adjacent mine in February 2015. Top slice production has been completed at the panel located in the middle, as shown in Figure 15. During development of the nearest panel to the old workings of Karanlıkdere mine, gas control boreholes were drilled, as seen in Figure 16.

As shown in Table 3, after drilling 24, 15, and 12 m, concentrations of CH_4 and CO_2 were found to be above the detection limits. Unfortunately, it was not possible to learn the exact gas concentrations. This can be considered as an indication of gas accumulation in the caved regions of the old workings of Karanlıkdere mine. It is probable that the caved regions of Karanlıkdere mine have been interconnected due to caving during production of the middle panel at the new adjacent mine. This might have resulted in the escape of some CH_4 to the surface through newly-formed subsidence cracks. It is also possible that a connection between these two mines might have been created, forming an air passage way between these mines. It is suggested that these phenomenon should be further investigated. It is also suggested to open methane drainage surface boreholes, especially above panel D and panel H of Karanlıkdere mine before commencing the production activity at the mine.

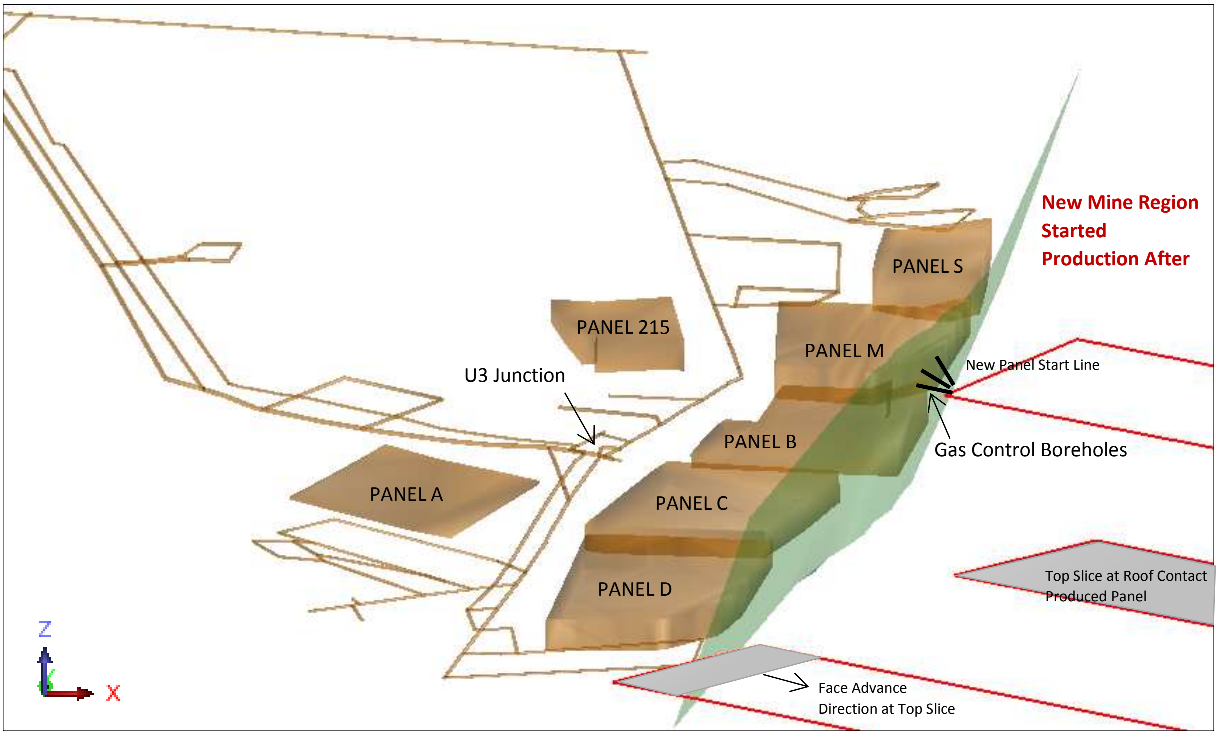


Figure 15. Location of Karanlıkdere mine and panels of the new adjacent mine.

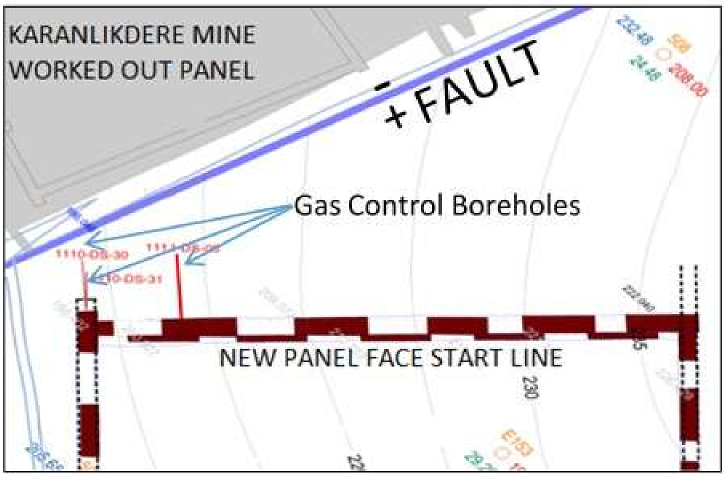


Figure 16. Locations of gas control boreholes opened towards old workings of Karanlıkdere mine.

Table 3. Gas measurement results obtained from control boreholes.

Borehole Code: 06 N311.5,horizontal					Borehole Code: 30 N311.5,3 Upward					Borehole Code: 31 N311.5,25 Upward				
Length (m)	Formation	CH_4	CO_2	CO	Length (m)	Formation	CH_4	CO_2	CO	Length (m)	Formation	CH_4	CO_2	CO
4	Coal	0	0	0	5	Coal	0	0	0	4	Coal	0	0	0
9	Coal	0	0	0	11	Coal	0	0	0	8	Coal	0	0	0
14	Coal	0	0	0	15	Coal	**	**	0	12	Coal	**	**	0
18	Coal	0	0	0	20	Coal	**	**	0	14	Rock	**	**	0
24	Coal	**	**	0										
29	Coal	**	**	0										
31	Coal	**	**	0										
34	Coal	**	**	0										

**Measurement above detection limit ($CH_4 > 5\%$; $CO_2 > 5\%$).

11. Conclusions

The Eynez field is the most valuable lignite resource in Turkey in terms of amount and quality. Therefore, it is a must to develop a safe and efficient production method. However, the history of underground mining at mass scale in the Eynez field is not long. Depletion of coal resources suitable for surface mining necessitates the use of underground mining. Unfortunately, the production amounts have increased without having enough technical information on the significant factors such as roof caving characteristics, methane drainage, and coal seam liability to spontaneous combustion.

An investigation of subsidence observed on the surface above panels C and D clearly reveal that there are empty spaces in the roof created due to bed separation. As a matter of fact, this is a usual occurrence in the field, in general. A sudden caving at the roof of an old working area located nearby the fire start location must have led to leaking of methane towards the main roadways. An inadequate design of protective pillar left to support main roadways in the mine resulted in the formation of a disturbed zone due to fracturing caused by over-stressing. This phenomenon supplied passage ways for pressurized methane formed in the roof of the worked-out panels. The risk of the uncaved roof having a potential to result in such a disaster has been pointed out in the past [24]. There is a need for an extensive research work for both to understand the details of disaster mechanism and for maintaining a major safety problem free operation in the future [25]. Research works on the following subjects must promptly be started [26]:

- Roof caving mechanism and its relation with subsidence must be fully determined and continuously monitored. Geophysical techniques can be used to point out any void over-production areas. Progress of roof caving and its behavior and stability conditions in mine should be continuously monitored by the 3D passive seismic method.
- Safe, efficient, and technological production methods and strategies must be developed.
- Methane contents of coal seam and surroundings have to be determined, and consequently, methane content distribution block models should be obtained. Methane flow and drainage details must be pointed out.
- Coal seam liability to spontaneous combustion should be determined for the whole seam stamp and depending on the location. Then mine fire risk zones could be determined.
- Stress-strain analyses of all development works, pillar stability, and especially production steps must be examined by extensive numerical modelling.
- Ventilation network analysis coupled with mine monitoring data should be automatically performed. Air flow through goaf should be modelled, and necessary monitoring techniques should be utilized for an early detection of spontaneous heating. Mine fire preventive measures and firefighting techniques should be extensively studied.
- The Computational Fluid Dynamics (CFD) technique should be used to analyze the progress of mine fire, and the results obtained should be taken into account for determining the correct evacuation strategies in the future.

Conditions that led to the disaster in Soma are also present in most of the coal mines in Turkey. Necessary scientific studies have to be started immediately. The only way for not relapsing the Soma disaster is to work properly in accordance with the mining science and technology.

Acknowledgments

Our heartfelt condolences go out to the families of the 301 men killed in the Soma Karanlıkdere mine disaster.

The possible mechanism of Soma mine disaster was submitted in the report submitted to Turkish Parliament (https://www.tbmm.gov.tr/sirasayi/donem24/yil01/ss680-bolum-1.pdf). The authors of this paper were the committee members. This paper puts all available data together for the assessment of the disaster.

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References

[1]. Saffari, A., Sereshki, F., Ataei, M. and Ghanbari, K. (2013). Applying rock engineering systems (RES) approach to evaluate and classify the coal spontaneous combustion potential in Eastern Alborz coal mines. Int. Journal of Mining & Geo-Engineering. 47 (2): 115-127.

[2]. Saffari, A., Sereshki, F., Ataei, M. and Ghanbari, K. (2017). Presenting an engineering classification system for coal spontaneous combustion potential. International Journal of Coal Science & Technology. 4 (2): 110-128.

[3]. Nebert, K. (1978). Soma Neogen Region That Contains Lignite, West Anatolia. MTA Dergisi. 90: 20-69. (in Turkish).

[4]. Ünver, B., Tercan, A.E., Hindistan, M.A., Ertunç, G., Atalay, F. and Ünal, M.S. (2011). Coal Seam Modelling and Mine Design at Eynez Lignite Site, Project Report Submitted to Turkish Coal Enterprises. 235 P. (in Turkish).

[5]. Tercan, A.E., Ünver, B., Hindistan, M.A., Ertunç, G., Atalay, F., Ünal, S. and Kıllıoğlu, Y. (2013). Seam modeling and resource estimation in the coalfields of western Anatolia. International Journal of Coal Geology. 112: 94-106.

[6]. Ünver, B., Çetiner, R., Namlıtürk, C. and ve Yalman, O.İ. (1991). Application of mechanization at Eynez Colliery. 12th Mining Congress of Turkey, Ankara. pp. 99-116 (in Turkish with English Abstract).

[7]. Ünver, B., Hindistan, M.A., Tercan, A.E., Ertunç, G., Ünal, M.S., Kıllıoğlu, S.Y. and Atalay, F. (2015). A New Production Method Proposal for Soma Eynez Coal Field Proceedings of the 24th Int. Mining Cong. Of Turkey, April 14-17, 2015 Antalya/TURKEY. pp.363-371 (in Turkish with English Abstract).

[8]. Anon, (2014). Determination of health and safety preventive measures at mining sector by investigation mine accidents happened primarily at Manisa province Soma town on 13th May 2014, Investigation Report of Turkish Parliament (TBMM) 2 Volumes (in Turkish) https://www.tbmm.gov.tr/sirasayi/donem24/yil01/ss680-bolum-1.pdf

[9]. Ünver, B. (1996). Possibility of efficient application of semi-mechanization in longwall mining in thick seams. Journal of Mines Metals and Fuels. pp. 223-230.

[10]. Ünver, B. (1997). Increasing the Efficiency of Production in Thichk Coal Seams Produced by Sublevel Caving. 15th Mining Congress of Turkey, 6-9 May, Ankara. pp. 179-183 (in Turkish with English Abstract).

[11]. Ünver, B. (1995a). A Practical Approach to Strata Control and Caving Mechanism in Thick Seam Coal Mining" 14th Mining Congress of Turkey, Ankara. pp. 15 - 22. (in Turkish with English Abstract).

[12]. Ünver, B. (1995b). An Investigation into Structural Geology and Geotechnic of Eynez Colliery. Bulletin of Turkish Rock Mechanics Society, June. pp. 27-40 (in Turkish with English Abstract).

[13]. Yaşıtlı, N.E. and Ünver, B. (2004). Numerical modelling of top coal caving in thick seam coal mining. EUROCK 2004 & 53rd Geomechanics Colloquium. Schubert (ed.).

[14]. Yasitli, N.E. and Ünver, B. (2005). 3D numerical modeling of longwall mining with top-coal caving. International Journal of Rock Mechanics and Mining Sciences. 42 (2): 219-235.

[15]. Unver, B. and Yasitli, N.E. (2006). Modelling of strata movement with a special reference to caving mechanism in thick seam coal mining. International Journal of Coal Geology. 66 (4): 227-252.

[16]. Vakili, A. and Hebblewhite, B.K. (2010). A new cavability assessment criterion for longwall top coal caving. International Journal of Rock Mechanics and Mining Sciences. 47 (8): 1317-1329.

[17]. Zhang, D., Qi, X., Yin, G. and Zheng, B. (2013). Coal and rock fissure evolution and distribution characteristics of multi-seam mining. International Journal of Mining Science and Technology. 23 (6): 835-840.

[18]. Ju, J. and Xu, J. (2015). Surface stepped subsidence related to top-coal caving longwall mining of extremely thick coal seam under shallow cover. International Journal of Rock Mechanics and Mining Sciences. (78): 27-35.

[19]. Yu, B. (2016). Behaviors of overlying strata in extra-thick coal seams using top-coal caving method. Journal of Rock Mechanics and Geotechnical Engineering. 8 (2): 238-247.

[20]. Aksoy, C.O., Kucuk, K. and Uyar, G.G. (2016). Long-term time-dependent consolidation analysis by numerical modelling to determine subsidence effect area induced by longwall top coal caving method. International Journal of Oil, Gas and Coal Technology. 12 (1): 18-37.

[21]. Ünver, B. (1993). Drivage of an Air Return Raise by Using a Combination of Monorail and Winch Transportation Systems, 13th Mining Congress of Turkey, Istanbul. pp.1-8 (in Turkish with English Abstract).

[22]. Anon, (2015). http://www.fireengineering.com/articles/print/volume-158/issue-9/features/the-art-of-reading-smoke.html.

[23]. Aktaş, E.Ö. (2014). Report to Turkish Parliament Investigation Commission, Forensic Medicine Institute İzmir Group Presidency.

[24]. Ünver, B. (2008). An Expert Report Submitted to Turkish Coal Enterprises on Park Technique Operations. Unpublished. 10 P.

[25]. Ünver, B. and Hindistan, M.A. (2010). An Assessment Report on Panel Closed due to Methane Emission at Eynez Karanlıkdere Coal Mine, Submitted to Turkish Coal Enterprises. Unpublished. 19 P.

[26]. Ünver, B. (2014). What to be done in Soma, Madencilik Türkiye (in Turkish).

تجزیه‌وتحلیل مکانیسم و علت احتمالی در حادثه معدن Soma

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چکیده:

یک فاجعه معدنی در تاریخ ۱۳ می ۲۰۱۴ در معدن Soma باعث شد ۳۰۱ نفر از معدنچیان جان خود را از دست بدهند. اطلاعات مختصری در مورد معدن زغال‌سنگ Eynez و برخی از ویژگی‌های ذاتی این منطقه زغالی و تأثیرات آن‌ها در معدنکاری ارائه شده است. این پژوهش اساساً بر روی عوامل مؤثر بر وقوع این فاجعه تمرکز دارد. آتش‌سوزی بدون هیچ گونه نشانه‌ای در قلب معدن به طور ناگهانی شروع شد. رخداد ناگهانی آتش‌سوزی و مشخصات آن نشان می‌دهد که علت اصلی این فاجعه احتمالاً مربوط به گرم شدن خود به خودی زغال‌سنگ است. تجزیه‌وتحلیل مکانیسم تخریب سقف، پروفیل‌های نشست، میزان تولید و شرایط کلی معدن نشان داد که آتش‌سوزی احتمالاً ناشی از تخریب ناگهانی در نزدیکی و بالای پهنه‌های استخراج قدیمی ایجاد شده است. تخریب بالایی، فشار گاز موجود در حفره‌ها و عدم تحکیم مناسب در ناحیه‌های تخریب شده افزایش یافته و گاز از حفره‌ها به سمت معدن جریان یافته است. گاز خروجی تحت فشار متوسط احتمالاً توسط یک موتور مانند موتور نوار نقاله آتش گرفته و آتش‌سوزی در معدن را منجر شده است.

کلمات کلیدی: معدن Soma، آتش‌سوزی در معدن، جبهه کار طولانی با تخریب زغال‌سنگ بالایی، کنترل لایه‌ها، نشست.