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Prediction and control of spontaneous combustion in thick coal seams

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PREDICTION AND CONTROL OF SPONTANEOUS COMBUSTION IN THICK COAL SEAMS

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ABSTRACT: Spontaneous combustion is one of the causes of fire in underground coal mines especially in thick coal seams, which may cause loss of working personnel, production, valuable reserves, and damage or loss of expensive mining equipment. The blasting gallery method in an 11 m thick seam in Indian geological conditions was considered to model prediction and control of spontaneous combustion (sponcom) in thick coal seams. To find sponcom properties of the coal, gas evolution test, sponcom propensity test, differential scanning calorimetry and crossing point temperature tests were conducted for the specified thick seam. The knowledge of goaf gas behaviour in the blasting gallery extraction method during sponcom can be useful in controlling and minimizing the effects of fire. The paper discusses the application of computational fluid dynamic simulations to investigate the goaf gas behaviour at the time of sponcom in the blasting gallery panels. Computational fluid dynamic simulations studies were also conducted with ascentional and descentional ventilation systems with inert gas injection at a single injection point, multiple injection points and at various inert gas flow rates. The results indicate that the descentional ventilation system is useful for goaf inertisation and multiple inert gas injection points are more effective than the single point injection. The paper also presents the effect of sealing of bottom rooms by inertisation.

INTRODUCTION

Charbonnages de France, a French mining company developed a method called Blasting Gallery (BG) to extract a thick coal seam at its Carmaux Colliery. The method is more suitable for thick seams up to 15 m height where the seam is already developed by the bord and pillar system (Yarlagadda, *et al*., 2011). The main advantage of this method is the high percentage of recovery (up to 85%) with less capital investment. However, if the coal seam is highly susceptible to sponcom then this method has fire and explosion issues. In this case, there will be a loss of production, machinery and coal reserves. The present paper discusses a case study taken from an Indian coal mine which has various sponcom tests details and a record of sponcom control measures adopted for its thick seam BG panel.

GDK 10 Incline Mine

GDK10 Incline mine of Singareni Collieries Company Limited (SCCL) is located in the southern part of India. The mine has two workable seams (III seam and IV seam). The thickness and gradient of the III seam are 11 m and one in seven respectively. Since 1987 the BG method has been employed to extract the coal reserves in III seam. The panel areas of III seam BG panels vary from 9000 m^2 to 33 000 m^2, which depend on the incubation period of the coal, strata condition and availability of machinery. Figure 1 shows the layout of III seam BG panel. It has 12 workable pillars of 40 m X 48 m size surrounded by barrier pillars. The width and height of the galleries (road ways) are 4.8 m and 3 m respectively. The roadways at barrier pillars are closed with explosion proof or temporary stoppings. Middle level (58L) is a haulage road to transport men and material and both 57L and 59L are used for belt conveyor. Air flow quantity of 40 m^3/s is used to ventilate the panel. The ventilation control devices like brattice and ventilation doors are used to send sufficient intake air to all the working places in the panel. During depillaring the pillars are divided into two stooks/slices, which are extracted by drilling long holes with jumbo drills and blasted with special type of explosives. Remote control operated load haul dumpers (LHD) are used to load and transfer the blasted coal.

COAL SEAM SPONCOM CHARACTERIZATION

The spontaneous combustion of coal seam is dependent on various factors such as moisture content, rank of coal, availability of oxygen, temperature, geological disturbances, ventilation, etc. The sponcom

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laboratory tests provide background understanding of how coal reacts with oxygen. The III seam sponcom propensity tests were conducted in India and Australia, and the results are discussed below.

Gas evolution test

The Gas evolution test (GET) was carried out to know the gas evolution parameters of a coal seam under oxidation conditions, and to develop fire indicators which can indicate the different stage of heating that happens in a coal seam (Clarkson, 2009). Approximately 70 grams of coal was placed in the sponcom vessel in the hot storage oven. A thermocouple placed in the centre of the spontaneous combustion vessel was used to monitor the coal temperature while a second thermocouple monitored the vessel temperature. Wet air was flowed through the vessel at approximately 10^{-6} m^3/s. The coal was heated in 20^oC steps to approximately 160^oC and then a 40^oC step to approximately 200^oC at 0.4^oC per minute. The temperature was maintained at each step while gas samples were taken for chromatographic analysis. The GET of III seam was conducted at the SIMTARS coal testing laboratory. Figure 2 indicates that CH_4, CO_2, CO percentages are increasing with the increase in temperature. The percentage of H_2 increases from 50^oC to 180^oC and after 180^oC it decreases. On the other hand, O_2 percentage decreases with increase in temperature to zero above 210^oC.

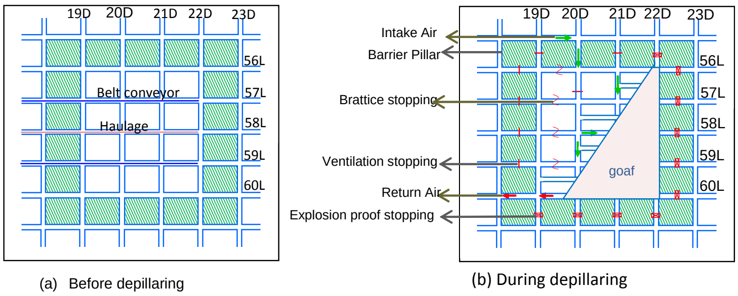
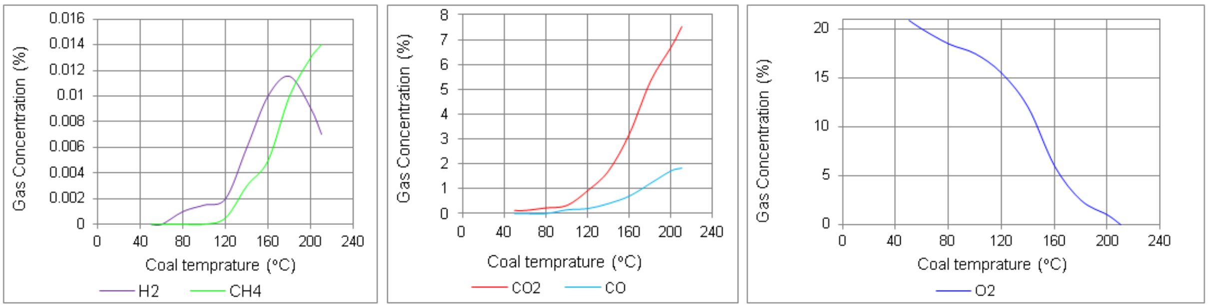


Figure 1 - Layout of the BG panel



(a) Methane and Hydrogen **(b) CO_2 and CO** **(c) Oxygen**

Figure 2- Gas evolution behaviour for GDK 10 Incline coal seam

Based on the gas evolution test, several sponcom indicators like CO/O_2 ratio, Graham's ratio, Morris ratio and young's ratios were derived for the III seam and are furnished in Table 1.

Table 1 - Indicator ratios derived from gas evolution test

Temperature (^oC)	47.8	65.4	85.2	105.8	129.6	154.7	173.5	211.0
O_2 deficiency	0.18	0.34	0.96	3.160	6.790	13.79	19.42	20.47
Graham's ratio	1.10	1.50	1.78	2.200	3.130	4.230	6.270	9.110
Morris ratio	5.34	11.6	18.0	24.04	23.23	19.66	14.08	9.460
CO/O_2 ratio	0.03	0.06	0.08	0.130	0.190	0.220	0.240	0.250
Young's ratio	0.27	0.23	0.20	0.160	0.160	0.180	0.250	0.360

Sponcom propensity test

Coal samples of III seam were tested at the University of Queensland sponcom test laboratory to determine R70 values. The coal samples were brought to the ambient start temperature of 40^oC by flushing with inert N_2; after achieving the study state temperature, O_2 was allowed to pass through the sample. The oxidation of coal continuous and the temperature of the sample rose linearly up to a temperature of 70°C. The time taken for the coal temperature to reach 70°C was used to calculate the average self-heating rate for the rise in temperature. This is known as the R70 index, which is in units of °C/h and is a good indicator of the intrinsic coal reactivity towards oxygen (Beamish, 2009; Beamish, *et al*., 2012).

The R70 values of coal samples with percentage of ash content are shown in Figure 3 and Table 2. The R70 values of the mining seam are in between 0.91°C/h to 3.63°C/h; the results show that the samples are reactive towards O_2, and their intrinsic spontaneous combustion propensity rating varies throughout the seam profile (Beamish, 2009). There is a distinct increase in coal self-heating temperature at the top (sample-1) and the bottom (sample-5) which shows that the samples are relatively more reactive than the middle section sample (sample-3); which may be due to the presence of high ash content in excess of 50%.

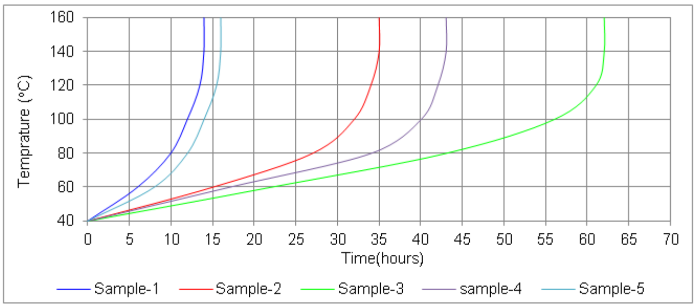


Figure 3 - Adiabatic self-heating curves for III seam samples of GDK10 incline mine

Table 2 - Results of sponcom propensity test

Sample	Location of the sample (III Seam top to bottom)	Ash content (% Dry Basis)	R70 (°C/h)
Sample-1	1.1 m	19.4	3.63
Sample-2	3.3 m	17.3	1.32
Sample-3	5.5 m	51.8	0.91
Sample-4	7.7 m	15.8	1.11
Sample-5	11 m	18.9	2.88

Differential Scanning Calorimetry (DSC) and Crossing Point Temperature (CPT) tests

In this test, coal samples are subjected to a controlled temperature where the energy inputs are measured and compared as a function of temperature (Mohalik, *et al*., 2009). The DSC thermo gram onset temperature of III seam coal is 61.52°C. The low onset temperature indicates that the coal seam is prone to spontaneous heating.

The rate of rise in coal temperature during coal oxidation becomes greater under favourable conditions. The temperature at that point where the coal temperature begins to exceed the surrounding temperature is called CPT. Since 1974 this test is most commonly used to find out sponcom propensity of coal seams in Indian coal mines. A coal seam with CPT 160°C and moisture content of 2% is poorly susceptible to sponcom whereas coal seam with CPT 140°C - 160°C and with moisture content of 2%-5% is moderately susceptible. A coal seam with CPT 120°C - 140°C and moisture content of more than 5% is highly susceptible to sponcom. The CPT and moisture content of III seam coal were found to be 138°C and 7.5% respectively. The results of the CPT along with proximate analysis of DSC thermo gram are shown in Table 3. The DSC and CPT tests were conducted at the Central institute of Mining and Fuel Research (CIMFER), India.

EARLY STAGE SPONCOM PATTERNS IN THE BG GOAF

The main reason for sponcom development in extraction panels is the presence of coal and high percentage of O_2 in the goaf region. Geological disturbances, shale bands, improper drilling and blasting, inefficient loading, and leaving coal in the form of curtains can leave a significant amount of coal in the goaf regions. Similarly, pressure variations between ventilation stoppings, unproductive ventilation system and inefficient inertisation are the reasons for the presence of high O_2 percentages in the goaf regions.

Computational Fluid Dynamic (CFD) simulation studies were conducted to simulate the airflow patterns in BG goaf with 40 m^3/s airflow quantity as boundary condition. The predicted gas distribution pattern of CO during early stage of development of sponcom is shown in Figure 4.

Results indicate that the amount of CO produced from heating at the goaf corner (22D/60L) would disperse over a wide area in the BG goaf. Even when the concentration of CO reaches 3% in the goaf, the return air CO levels were only around 1 ppm. Therefore, it is critical to monitor CO levels in the goaf for early detection of sponcom in the goaf area. In order to control/regulate the sponcom, simulations were carried out with effective inertisation using CO_2 gas.

Table 3 - DSC thermo gram results of GDK 10 Incline coal seam

DSC results of III seam of GDK10 Incline mine	
Crossing point temperature	138°C
Ignition point temperature	157°C
Percentage of mixture content	7.50
Percentage of ash content	11.1
Percentage of volatile matter	31.6
Percentage of fixed carbon	49.8
Percentage of Pyritic Sulphur	0.10
Percentage of organic Sulphar	0.13

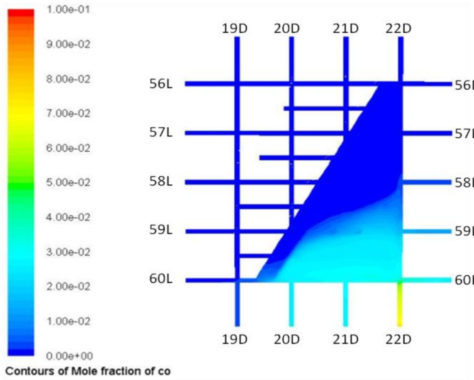


Figure 4 - Early stage of spontaneous combustion in the goaf

DEVELOPMENT OF PROACTIVE SPONCOM CONTROL STRATEGIES

Ventilation

Airflow quantity of 40 m^3/s was taken as a boundary condition for this model. Figure 5 shows the O_2 distribution pattern in the BG goaf region for both ascentional and descentional ventilation systems. From the figure, it can be seen that in both cases, the O_2 percentages are high. CH_4 is a lighter gas, and its specific gravity is 0.554 so it tends to escape from the topmost levels/dips of a goaf. In the descentional ventilation system, CH_4 moves opposite to the air flow direction hence, there is less goaf airflow flush and offers advantages for goaf inertisation. In an ascentional ventilation system both CH_4 and air move in the same direction hence, O_2 concentration in the goaf is very high.

Inertisation from a seal

In longwall mines, various inertisation techniques at different locations and with various flow rates and gases are available (Balusu, *et al*., 2005; Ren, *et al*., 2005; Claassen, 2011). Mine ventilation simulation softwares are also available to simulate the inertisation and mine fires (Gillies and Wu, 2007).

Figure 6 shows the inertisation results when 0.03 m^3/s of CO_2 was injected from upper level (left figure) and middle level (right figure) of the panel. The modelling results show that the inert gas injection via seal

56L/22D has little impact on goaf; CO_2 dissipated along the air flow and O_2 level remains above 19% in most of the goaf regions. However, improved inertisation can be achieved by injecting CO_2 through the middle part of the goaf, i.e., 58L/22D.

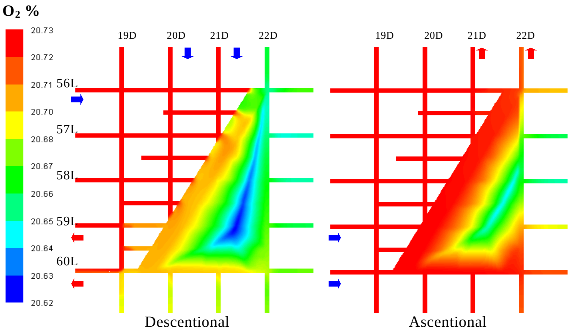


Figure 5 - Oxygen distribution patterns in the goaf area for panel with descentional and ascentional ventilation systems (Yarlagadda, *et al*., 2011)

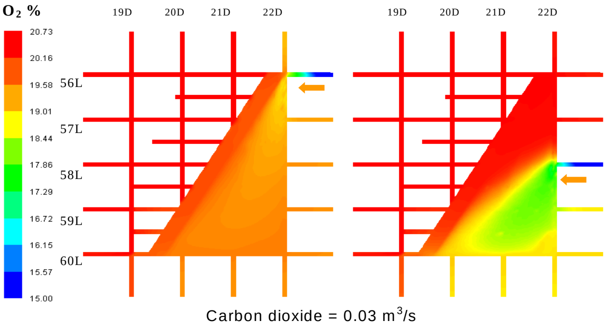


Figure 6 - Inertisation results by injecting CO_2 via seal 56L/22D and 58L/22D with 0.03 m^3/s injection rate

Inertisation with different CO_2 injection rates

Figure 7 shows the injection of CO_2 at the middle level from 58L/22D with flow rates of 0.03 m^3/s and 0.1 m^3/s respectively. It can be seen that there is no variation in O_2 percentages in the goaf and most of the inert gas was flushed out through the return air. It shows that the inert gas injection location is very important for efficient goaf inertisation.

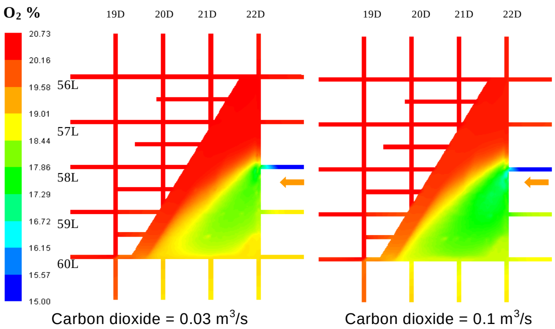


Figure 7 - Comparison of goaf inertisation results with different CO_2 injection rates (0.03 m^3/s VS 0.1 m^3/s)

Inertisation from multiple seals

Figure 8 shows the inertisation from a combination of injection points, such as 56L/22D, 58L/22D and 60L/22D. The results show that improved concentration of CO_2 in the goaf, and significant amount of CO_2 (5%) is in the working face of the goaf. At the goaf corner, the percentage of O_2 is reduced to 17%. The inert gas injection from the multiple points (Figure 8) with 0.03 m^3/s was achieved better goaf inertisation than the single injection point with same flow rate (Figure 6). From the figure, it is clear that the multiple injection points are more effective than the single injection point.

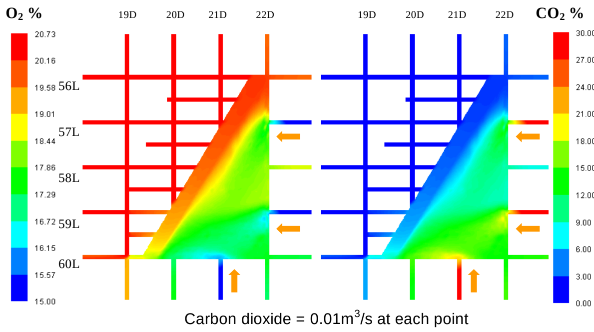


Figure 8 - Inertisation results by injecting CO_2 via multiple seals 56L22D, 58L22D and 60L22D with 0.01 m^3/s injection rate at each point

Rooms closed at lower part of the BG panel

Figure 9 shows the inertisation from 57L/22D, 59/L22D and 21D/60L with 0.02 m^3/s injection rate at each point while rooms at 59L and 60L are closed, the simulation results show that inertisation from the multiple points with closing of bottom rooms cause better inertisation in the goaf region. In the goaf region the CO_2 percentage increased to 20% and O_2 percentage decreases to 15%. The concentration of CO_2 along the working face region also improved.

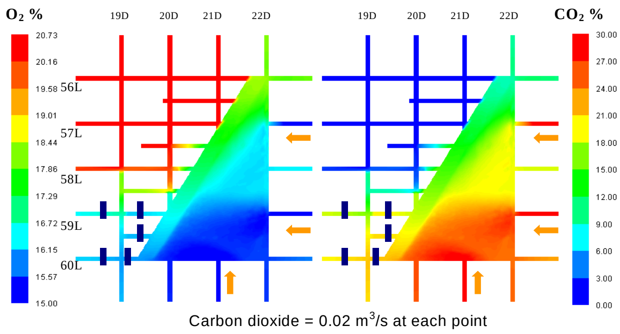


Figure 9 - Inertisation results by injecting CO_2 via multiple seals with 0.02 m^3/s injection rate at each point - rooms 59L and 60L sealed off

FIELD DEMONSTRATION STUDIES IN BG PANEL

Field studies were carried out with the descentional ventilation system at an air flow rate of 40 m^3/s. Inertisation with CO_2 was carried out from lower levels with an extensive gas monitoring system. Figure 10 shows the BG panel where the field trials were carried out along with the inertisation monitoring points (one to seven). The panel has nine workable pillars and about 9000 m^2 of area. The goaf inertisation was initiated about three months after starting of the panel. The inert gas injection rate was 2 t/d to 12 t/d. To improve the caving pattern, the induced blasting was enhanced by significantly reducing the blasting interval to 5 m and by increasing the depth of the blasting hole to 10 m.

The amount of inert gas injected into the panel with the increase in injection points throughout the working period of BG panel is shown in Figure 11. It shows that after 160 d, the amount of CO_2 injected was more than six tonnes per day, and the number of injection points increased to six.

During the initial stage, coal exaction was carried out from lower levels of the BG panel, however, the caving was not fully performed and the goaf was in the initial stage of formation for almost three months from the start of panel. The trends of O_2 and CO_2 at 60L/18D are shown in Figure 12. The results show that after 140 d (after bottom most rooms closed), the percentage of CO_2 increased sharply and there is a gradual reduction of O_2 percentage. During the panel extraction, traces of CO were not found.

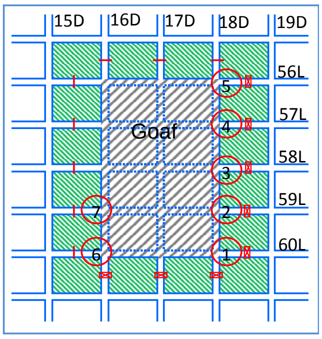


Figure 10 - Inertisation and monitoring plan of BG panel for field trails

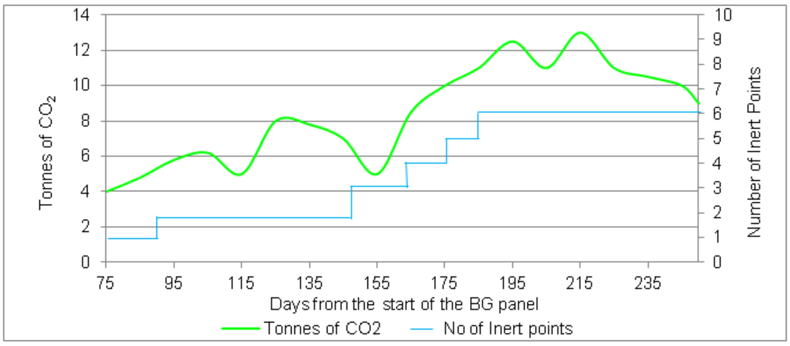


Figure 11 - Inert gas injection rate during panel extraction

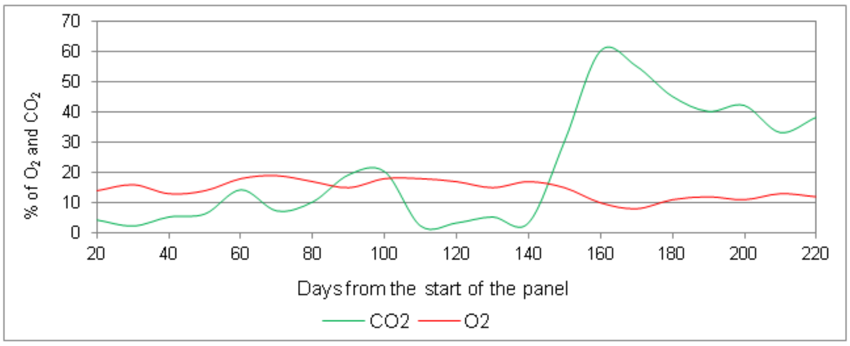


Figure 12 - O_2 and CO_2 percentages during the panel extraction

CONCLUSIONS

As per III seam coal sponcom laboratory investigations, the coal is highly prone to sponcom. The crossing point temperature of the coal is 138^{o}C. The R70 values of the coal seam vary from 0.91 to 3.63^{o}C/h. The DSC thermo gram onset temperature is 61.52^{o}C. GET values indicated increased percentages of CH_4, CO_2, CO and H_2 with increasing temperature and reduction in O_2 percentage with increasing temperature.

As per the CFD simulations, during early stages of sponcom, CO spreads in all direction from source. In descentional ventilation system CH_4 moves opposite to the air flow direction hence, less goaf airflow flush and offers advantages for goaf inertisation. The inertisation from the inbye locations of the goaf region is effective compared to the inertisation from the outbye locations. The multiple inert gas injection points cover more goaf area and provide efficient goaf inertisation compared to the single point inertisation. Inertisation by sealing the bottom most room provides effective inertisation.

Field studies demonstrated that descentional ventilation system with improved induced blasting pattern and effective inertisation from multiple points with bottom levels sealed off has enabled successful extraction of the panel without sponcom development in the goaf area.

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