A STUDY OF POTENTIAL FAULT REACTIVATION AND WATER INTRUSION AT A LONGWALL COAL MINE IN APPALACHIA

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ABSTRACT

A longwall coal mine in Appalachia about 1,500 ft deep encountered a fault while developing a new longwall panel. The fault extended from mining depth to the surface near a secondary road and drainage. The fault was located inside the anticipated angle of draw within the mined panel and gob. The fault extended vertically out and up, away from the panel, caved zone, and gob at nearly the angle of draw; the fault very nearly following the angle of draw. It was initially thought that "fault reactivation" could possibly occur. Fault reactivation is the phenomenon of having mining subsidence localized along a fault leading to a "reactivation" of the fault and shearing and displacement along the fault. Such fault reactivation would disrupt and deform the fault plane beyond the normal angle of influence of the subsidence trough, and may provide a conduit for any ground and surface waters to reach the mine.

We contacted all operators of longwall mines in Appalachia to determine if any Appalachian longwall mines had ever experienced fault reactivation, and learned that none had experienced the phenomenon. After studies of possible water intrusion quantities and rates based upon in-fault pump tests, which indicated that water intrusion rates should be manageable, and the prior experience that faults in this particular area were usually barriers to water flow, mining proceeded with caution and monitoring. Mining was successful with no noticeable increase in water inflow rates, and no measurable off-setting of the fault exposure on the surface. It can be concluded that the fault did not reactivate due to its relationship to the mining sequence.

INTRODUCTION

During development of a panel for an existing longwall mine in Appalachia, the mine encountered an unexpected high-angle normal fault in the southern gateroads of the panel, near the starting point of later longwall mining in the panel. Due to the position and orientation of the fault, concerns were expressed over the likelihood of the fault being disturbed by the strata movement, possibly "reactivating" (that is, exhibiting renewed movement), and providing a connection between the mine and the overlying aquifers, and possibly even surface waters.

Observation in the mine of the high-angle normal fault in the gateroads for the longwall panel revealed a fractured zone about 4 ft thick with a gouge zone of stiff-clay about one-half foot thick. The fault had a dip of 64º to the northwest in the mine.

Figure 1 shows the location of the fault as intersected in the mine and as ultimately located at the surface by geomorphological analyses and by drilling. Borehole 1 was drilled inside the surface projection of the fault from the mine location and dip, and did not intersect the fault. Based on these results, it was initially thought that the fault did not extend to the surface. However, geomorphological analysis revealed a possible surface trace lineament, so that Boreholes 2 and 3 were drilled and did intersect the fault, demonstrating its extension to the surface.

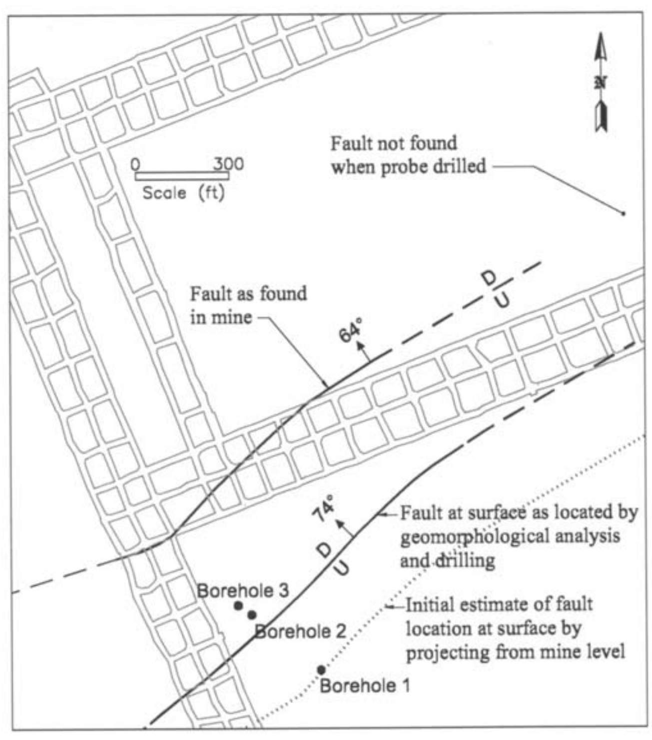

Figure 1. Map of Fault in Mine

The fault in the diamond drill cores of the boreholes has about one-half foot of tight clay gouge and shattered rock on the hanging wall, totaling approximately 4 ft in thickness perpendicular to the fault. Drilling proved the fault to extend to the surface at a dip, varying from 64° at the mine level to approximately 74° at the surface, over a vertical distance of approximately 1,500 ft.

The fault has 1 to 2 ft of displacement at the mine elevation and either no displacement, or strike-slip displacement, in Boreholes 2 and 3 at a depth of approximately 400 ft. The fault is downthrown to the northwest. To the northeast, the fault becomes undetectable inside the panel when probe-drilled in the seam. In the mine, the fault exhibits only drips of water, even though it is continuous to the surface and intersects several aquifers along its extent.

STRATA BEHAVIOR

When considering the effects of the longwall mining on the overlying strata, many researchers have described several zones of resulting strata deformation and fracturing above the mining, for example, Singh and Kendorski (1), Liu (2, as cited in Peng (3)), and modified most recently by Kendorski (4). These works have identified the zones above longwall mining as (from the mine up):

- Caved Zone: Collapse and disaggregation extending 6 to 10 times the mined thickness above the panel.
- Fractured Zone: Continuous fracturing extending approximately 30 times the mined thickness above the panel, allowing downward drainage of intersected surface and ground waters.
- Dilated Zone: Development of a zone of dilated (increased storativity) and leaky strata with little enhanced vertical permeability, from 30 to 60 times the mined thickness above the continuous fracturing zone and below the constrained or surface effects zones, whose thickness or existence is dictated by the zones above and below.
- Constrained Zone: Maintenance of a constrained, but leaky zone, above the dilated zone and below the surface effects zone, whose thickness or existence is dictated by the zones above and below.
- Surface Effects Zone: Surface fracturing extending 50 ft or so beneath the ground surface.

The depth of the mine and the thickness of the seam being mined indicate that the mining effects should not extend into any aquifers that could drain into the mine. However, no guidance was given on the potential for faults and their influence on these zones and water intrusions.

MSHA (Fredland et al., 5) suggests that if a fault is encountered or suspected, it ". . . should be thoroughly investigated for its potential for allowing flow into the mine." MSHA goes on in the same article to state:

> At greater mining depths, a sudden high inflow is less likely and the concern is more for a gradual increase in flow into the mine. In this case, the overall impact of inflow on the mine must be determined. This calls for examination of potential flow paths and depths in the mine.

HYDROGEOLOGICAL TESTING

From prior work at the mine it was known that, in addition to surface waters, there were at least two significant aquifers present which were termed the "shallow" and the "deep" aquifers. The aquifers interact weakly, but the shallow aquifer delivered significant quantities of water into the underlying mine when intersected by through-going fractures. However, it was known that faults in the area of the mine are usually aquitards or barriers to water flow. Therefore, the fault, if disturbed, could be considered a *possible* conduit into the mine for ground, and, remotely, surface waters.

A series of packer tests were conducted in Borehole 2, packing-off 10-ft and 19-ft intervals, intersecting the fault, with the top packer at 425 ft from the ground surface. Using the Hazen-Williams relationship, with a roughness value of 130 (as for 1-inch-diameter new steel pipe), gave hydraulic conductivity values of 1.4 to 17.7 ft/day. The 17.7 ft/day value results in an estimate of inflow of 180 gpm along the 2,000-ft trace of the fault at the mine horizon. It was considered that the flow could be replenished continuously by the aquifers and, possibly, surface waters.

As an alternative to the Hazen-Williams approach above, we also used the Equilibrium or Theim Equation (Theim (6) and Todd (7), cited in Davis and DeWiest (8, p. 203, eqn. 7.6)), where the hydraulic conductivity for the fault is as follows:

$$K = ((Q \times \gamma_w) / (2\pi \times L \times \Delta p)) \times \ln (r_e / r_w) \qquad (1)$$

where
K = hydraulic conductivity
Q = flow rate
γ_w = unit weight of water
L = length of borehole tested
Δp = water pressure differential during test
r_e = radius of effect of packer test
r_w = radius of borehole

Using the results from the packer test:

Q = 2.30 ft^3/minute
γ_w = 62.4 pcf
L = 10 ft
Δp = 10 psi (estimated)
r_e = 1 ft (estimated as drilled)
r_w = 10 ft (estimated)

results in K = 0.00365 ft/minute. Using Darcy's Law:

$$Q = K \times I \times A \qquad (2)$$

where
Q = flow rate
I = ΔH/ΔL
where ΔH = change in head in flow conduit
ΔL = change in length of flow conduit
A = area of flow conduit

using
K = 0.00365 ft/minute
ΔH = 945 ft
ΔL = 963 ft
A = 4 ft × 2000 ft

results in Q = 28.6 ft^3/minute or 214 gpm, which is in reasonable agreement with the Hazen-Williams approach. Such inflows are considered manageable by the mine.

These results are for the fault as tested, before any disturbance from longwall mining deformations. It may be expected that a fault, if disturbed in a dilational mode, could have its hydraulic conductivity increased.

FAULT POSITION AND REACTIVATION

The fault is located such that as the panel longwall is mined (beginning at the southwest end and progressing to the northeast (see Figure 1)), the fault will lie inside the angle of draw within the mined panel and gob. The fault extends vertically out and up, away from the panel, caved zone, and gob at nearly the angle of draw. It was initially thought that fault reactivation and disruption by the caving and developing subsidence trough could possibly occur. Fault reactivation is the phenomenon of having mining subsidence localized along a fault lead to a "reactivation" of the fault and shearing and displacement along the fault locally rather than the fault subsiding along with the strata that contain the fault. A sharp step or shear can then actually develop at the surface expression of the fault. Such fault reactivation would disrupt and deform the fault plane and may provide a conduit for ground and surface waters to reach the mine. Fault reactivation as a consequence of coal mine subsidence has been recognized for many decades (Griggs, 9, p. 121-123).

We contacted all operators of longwall mines in Appalachia to determine if any mines had ever experienced fault reactivation. NIOSH and MSHA personnel were also contacted. We learned that none had experienced fault reactivation. In fact, almost all mines carefully avoided faults in mining layouts. Only one operator had crossed a fault that they feared could reactivate, however, the fault did not reactivate. Fault reactivation has not been known to occur in Appalachia, nor anywhere in North America, to our knowledge.

In England, Lee (10) summarized a number of occurrences of fault reactivation from longwall and other full-extraction mining. Lee's (10) findings are that for English coal-measure strata (which are much softer overall than Appalachian strata), several factors must be present for fault reactivation to occur:

1. The fault must dip over the panel and toward the panel center with the panel in the footwall or hade of the fault.

2. The fault surface expression must be about 0.2 times the depth toward the gob from the solid-gob line or gateroads.

3. A longer fault is more prone to reactivation than a shorter fault, and a fault that does not completely cross a panel and extend well beyond its limits, is less prone to reactivation.

The first point provides that the fault must be in the area of the subsidence with the greatest deformation and dilation and, consequently, tensile strain. The fault that we studied is in the opposite position, extending up away from and over the panel, while the panel is still in the footwall of the fault.

The second point provides that the fault must be in the maximum tensile strain area of the subsidence trough between the gateroads and the trough center. The fault that we studied is, again, in the opposite position, being about 0.2 times the depth outside the gob from the solid-gob line or gateroads.

The third point provides that the fault completely cross the panel. This is logical because the end of the fault provides a restraint against reactivation by the unfaulted strata, requiring deformation or shearing of unaffected strata to continue fault reactivation laterally. The fault that we studied only extends a short distance into the panel before pinching out.

Thus, based upon English experience, the fault in question is at a minimum potential for reactivation and consequent disruption and deformation of the fault leading to an increase of hydraulic conductivity.

POTENTIAL FOR FAULT SHEARING

Whittaker and Reddish (11, p. 334) in discussing faulting's effects on subsidence, point out that

> Normal faults are considered to occur under a state of high vertical stress and relatively low horizontal stress thereby creating a net increase in lateral movement. Normal faults are most likely to move under the influence of mining because being a tensional feature, the two surfaces of the fault are potentially being pulled apart, and hence, friction plays a lesser role than in other fault types.

These concepts indicated the possibility of localized fault shear failure in the subsidence-influenced strata just under the longwall-developed pressure arch, where tensional or extensional strains are greatest, before the subsidence has progressed to the surface.

VALLEY RELIEF FRACTURE EXTENSION

Often where the mine workings are adjacent to or under surface waters, water intrudes from open fractures in the roof and ribs, usually peaks after a few days, and then diminishes to a small fraction of its peak. Such coincidence of water occurrences and surface waters is likely due to the "valley relief fracture extension" phenomena. Valleys overlying the mines in Appalachia are steep-walled, deep valleys eroded and incised over the millennia into the flat-lying, but faulted overlying sediments. The down-cutting of streams and rivers has allowed the valley walls and floor to become unloaded of their burden of overlying and adjacent rock and to expand, and, when relieved of the stress, cause dilation of the pre-existing fractures in the strata. This dilation increases the fracture's ability to store and transmit water. It has been demonstrated in Appalachia by USBM investigations (12, 13) that the relieved fracturing can extend hundreds of feet vertically and laterally from the valley floor and walls. This phenomenon may add to the possibility of increased hydraulic conductivity of the fault in question, if the fault pre-dates the erosional down-cutting and unloading of the strata.

The mine of interest in Appalachia also experienced increased water intrusion near and under valleys, indicating likely valley-relief phemonena.

CONCLUSIONS

The presence of a fault within at least a portion of the longwall panel, and its apparent continuity to the surface, passing through at least two aquifers, led to concerns about the fault being disturbed or reactivated by longwall mining strata deformations. If disturbed, the fault may no longer behave as a barrier to water flow, and may act, instead, as a conduit for ground and, possibly surface, waters to the mine. However, field hydrogeological tests indicated the fault could only provide water intrusions that were considered manageable. In addition, the fault's geometric relationship with the longwall mining and consequent subsidence features, based on English experience, strongly indicated that the fault would not reactivate, which was in agreement with modeled shearing stress results. Being in an area known to have valley relief fracturing and enhanced water intrusion into the mine, potentially exacerbated the potential for water intrusion, but, it was thought, not significantly.

With all of the above in mind, the mine decided to proceed with the longwall panel mining, with careful monitoring and observations.

The mine's experience during and after longwall mining through the fault was that:

1. Surface subsidence was observed 15 to 20 days after mining.

2. No displacement of the fault occurred.

3. The subsidence profile that was similar to that experienced over the mine's other longwall panels, with no stepping or offsetting of the fault at the surface.

4. No noticeable increase in water intrusion or pumping load was experienced in the mine.

5. No evidence of water entering the mine along the trace of the fault could be found.

We concluded, therefore, that the fault did not reactivate due to longwall mining, and was located with respect to the longwall panel, mining direction, and mining layout so that the fault followed the observations of Lee (10) in English mining situations.

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