SHEAR MECHANISM FOR MINING-INDUCED FRACTURES APPLIED TO ROCK MECHANICS OF COAL MINES

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ABSTRACT

Two examples of en echelon mining-induced fractures seen in hard-rock mines provided a basis for inferring that fracture zones and bedding plane separations immediately surrounding mine openings are promoted by oblique shear into the openings. It is hypothesized that initial fractures or separations form at the corners of openings as a result of high stress and physical constraint on the rock's ability to deform elastically toward the opening. These conditions result in a locally preferred direction of shearing. The shearing, in turn, generates tensile stress that initiates a progression of systematically offset fractures approximately parallel to the direction of greatest compressive stress. The fractures or bedding separations create tabular rock layers that amplify shearing displacement through bending and dilation. Such shearing effectively reduces and redistributes the compressive stress, but significant dilation is an inevitable consequence. The combination of dilation and shearing and the progressive development of fracture zones have important implications with respect to ground support.

The concept of mining-induced fractures forming as a result of shear is illustrated by two examples from coal mines. First, fractures seen at longwall faces probably result from shear associated with subsidence. The fracture zone that develops approximates or possibly defines the draw angle of subsidence. As the face advances, fractures extend downward along the lower edge of the fracture zone, while upper extensions of the fractures are pressed closed.

Fracture zones in entry roofs provide a second practical example. Here, mining-induced fractures typically follow bedding planes. The shear zone model suggests that the first bedding separations develop near the edges of the roof and successive separations progress upward and toward the center. However, if the direction of greatest stress is inclined with respect to the roof, a fracture or bedding separation zone may propagate from one side only and also extend higher. Because coal ahead of the face provides some support against lateral shear deformation, bedding separation is inhibited near the face. Rock bolts installed close to the face ultimately become more strained and bent than bolts installed a few meters from the face, and bolts installed through the more remote part of a separation zone may ultimately experience the greatest tensile and bending strains. This model is supported by field data documenting progressive bolt failures that rapidly propagated downward across the roof during face advance.

INTRODUCTION

Although mining-induced fractures are well known in coal mines, where they are associated with cave development and roof, wall, and pillar instability, our understanding of fractures and fracture zone development has been lacking. The classic explanation of mining-induced fractures is that they result from stress alone and form parallel to the direction of greatest stress. For example, it has been proposed that stress progressively splices together microcracks until they become continuous fractures, or that fractures propagate because compressive stress induces tension at their leading edges. Two examples of mining-induced fractures observed in hard-rock mines provided a basis for proposing that these fractures actually resulted from shear strain that developed as rock was displaced obliquely toward mine openings.

This paper first describes these two examples, which stimulated the author’s recent research on fracture development, develops a general hypothesis for fracture zone development, and applies the hypothesis to the formation of face and roof fracture zones in coal mines. I propose that application of the shear zone concept of fracture and bedding plane separation to coal mines may substantially aid our understanding of these phenomena and lead to improved mining and ground control practices.

MINING-INDUCED FRACTURES IN HARD-ROCK MINES

Example 1: Rock Burst in a Development Heading

A rock burst in an Idaho silver mine took place in the face of a development heading that was being driven normal to vertically dipping, massive quartzite beds (figure 1), creating a bowl-shaped cavity centered in the face. Inspection showed that the quartzite had been thinly split on the edges of the cavity (figure 2), but much of the broken rock ejected from the cavity was thicker than the quartzite at the edge of the cavity. Inspection of the walls after the next advance showed no evidence of splitting. Thus, the splitting was confined to the edge of the cavity and evidently represented

Figure 1. Cavity created by a face-strain rock burst in a development heading of a hard-rock mine.

Figure 2. Edge of burst cavity shown in Figure 1. Note closely spaced fractures.

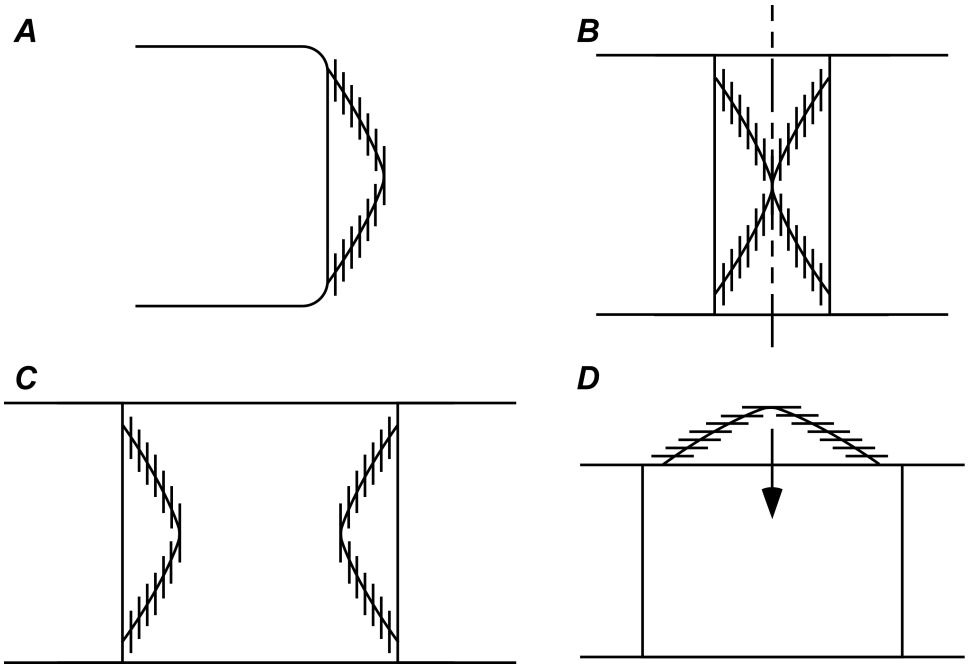

Figure 3. Cross sections of fracture zones in various settings. *A*, Cross section of face-strain burst shown in figures 1 and 2; *B*, compression test specimen; *C*, hour-glassing of pillars; *D*, inverted-V failure of entry roof.

many individual fractures that were progressively offset with depth along the cavity edge toward the center of the face (figure 3*A*). This contrasts with a classic view presented by Fairhurst and Cook (*1*) that mining-induced fractures extend all the way across a face or surface.

A cross section through the face (figure 3*A*) showed that the fracture distribution bore a striking resemblance to fractures formed in laboratory tests when the ends of the samples are constrained against expansion or slippage and en echelon fracture zones extend obliquely from opposite corners (figure 3*B*). Thus, the rock burst seemed to be a good field example of the laboratory test. The fractures in the laboratory specimens also resembled the fractures that cause hour-glassing in pillars (figure 3*C*) (*1*).

Another field example of this fracture pattern was described to the author at a western coal mine where a well-lithified, hard, brittle

A

B

Figure 4. Cut (or drift) in a steeply dipping hard-rock vein. *A*, View along wall. Photo taken while standing on sandfill from previous cut. Note mining-induced fractures and temporary friction rock bolts from roof of previous cut exposed in wall. *B*, View of wall showing bent rock bolt offset by shear displacement along en echelon fracture zone.

mudstone roof occasionally experienced inverted-V-type roof failures. The geometry described by mine personnel (figure 3*D*) suggested that the edges of these cavities were also formed of closely spaced bedding plane separations systematically distributed along what would eventually become the edge of the collapse.

These conclusions fired the author's interest in mining-induced fractures and led to several years of intensive study. However, a second notable observation in a hard-rock mine, described below, preceded this study.

Example 2: En Echelon Fracture-Shear Zone

This example (figure 4) is in a steeply dipping, narrow vein. The vein is mined by the overhand method, which involves mining the vein in a horizontal cut or drift, filling the cut with sand, and then driving a new cut on top of the sand. Thus, mining advances along a longwall front in an ore body that stands on end.

Split-Set[1] rock bolts provide temporary support during the mining of each cut. Since the vein was not quite vertical, each cut was slightly offset from the one preceding, so that bolts installed in the roof of the previous cut were sometimes exposed in the next cut above (figure 4). High stress around the ends of the mined portion created horizontal fractures that became exposed in the walls and face of each new cut (figure 4*B*). In figure 4*B*, a rock bolt from the previous cut intersects fractures that were induced by mining, as shown by shearing offset of the bolt. It is also evident that the fractures involved are not continuous, but form a zone of systematically offset, or en echelon, fractures. Such fracture zones have been found to be common in the deep hard rock mines of Idaho.

The observation that the fracture zone experienced shear is consistent with the fractures having resulted from high horizontal stress. Shearing effectively reduced the magnitude of the stress. The mechanics of shearing evidently involve bending of the rock layers (figure 5). Bending, in turn, causes dilation as the end of each layer is lifted away from its substrate. Hence, it may be concluded that the stress that causes the fractures is reduced at the expense of shearing and dilation, with a net displacement that is oblique to the fracture zone. However, extensive shear displacement only occurs after fractures have formed. Therefore, the fracture zone must actually result from shear displacement that originates prior to fracturing, when conditions are still elastic. There appears to be no alternative to this interpretation.

Gramberg (*2*), who spent a lifetime studying fractures, concluded that extension fractures result from "induced tension" caused by compressive load parallel to the fracture. If so, it may be reasonable to consider that the origin all extension fractures caused by compressive stress is the same, even when no discernable en echelon arrangement is evident, and that they all ultimately result from shear strain, which is actually responsible for the "induced tension."

This leads to a general explanation of mining-induced fractures, which may be stated in the form of a hypothesis.

SHEAR HYPOTHESIS FOR MINING-INDUCED FRACTURES

A general explanation for the origin of mining-induced fractures is stated as follows:

1. Asymmetric elastic distortion about mine openings manifests shear;
2. Shear causes diagonal tension, which is directly responsible for creating mining-induced fractures;
3. A fracture zone propagates en echelon fractures along the direction of shearing.

Since a rigorous and convincing demonstration of this has not been presented and has not even been published, this explanation will be offered as a hypothesis, although a strong case can be made in its support.

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[1]Mention of specific products or manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

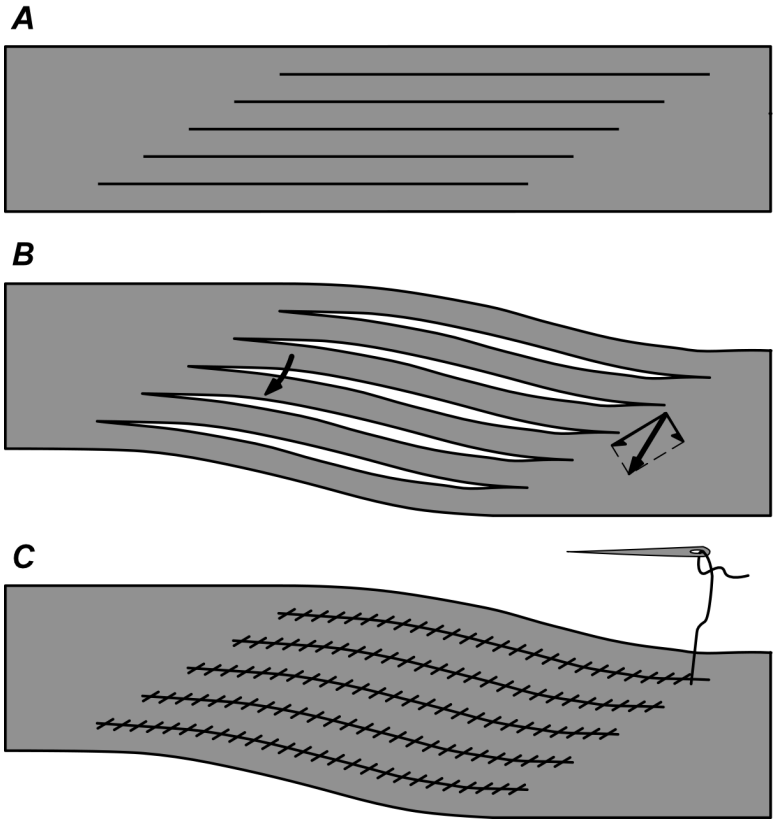


Figure 5. Displacement mechanics along en echelon fractures. *A*, En echelon fractures with intervening layers; *B*, combined dilation and shear displacement resulting from rock layers rotating away from adjacent substrates; *C*, fractures zone "repaired" with imaginary needle and thread. Both stitches and layers are under tension, thereby illustrating the origin of the tensile stress that causes fractures.

This explanation for mining-induced fractures contrasts with the prevailing view that such fractures form parallel to the direction of greatest stress as a result of this stress alone (figure 6*A*). The explanation advocated here is that the fractures result from shear strain caused by load and by distortion resulting from the presence of a nearby mine opening. In general, this distortion happens at corners or edges of mine openings because the openings create a preferred direction of displacement that takes the form of shear (figure 6*B*). The shear, in turn, generates diagonal tension approximately parallel to the direction of least stress, and extension fractures result.

The simplest illustration of this idea can be seen when a reference shape, such as a square, is deformed into a parallelogram by shearing along two opposite sides. The diagonal distance between opposed acute corners increases and represents extension. Near mine openings, the extension becomes tension. Alternatively (figure 5*C*), we can imagine "repairing" the open fractures of Figure 5*B* with an imaginary needle and thread. If so, it is evident that both thread and rock layers are in tension.

Along originally straight edges of mine openings, the fundamental shape is a flattened S (figure 5*B, C*). The direction of greatest stress crosses the S at a low angle, so a fracture that forms parallel to the opening actually experiences a little bit of shear stress. Consequently, mining-induced fractures don't result strictly from tension. A little shear displacement occurs, not enough to see without careful measurment, but enough to aid significantly in the formation and propagation of each fracture.

Typical modeling exercises that identify compressive and shear stress concentrations near corners of openings suggest that "shear zones" are initially highly foreshortened. Hence, mining-induced fractures do not all form at once, but in succession. Once a fracture forms, it isolates a layer of rock, and stress is redistributed and reduced within the layer. Stress continues to be redistributed deeper into the rock, and a new fracture is formed, and so on. The geometry of the situation is such that each new fracture is translated sideways from the previous one, tending to propagate a zone of fractures that are distributed en echelon.

One way of looking at fractures that is especially relevant for roof rock in coal mines is by comparing them to the geologic structures known as kink bands (figure 7). Empirically, kink bands form in layers that possess high interlayer friction (*3*). A kink band solves the friction problem by dilating the layers within the kink band. The dilation is a simple consequence of the geometry, the dimension normal to the layers increasing within—as compared to outside—the band, so that the layers separate enough to reduce or eliminate friction. In a similarly deformed, unlayered material, the

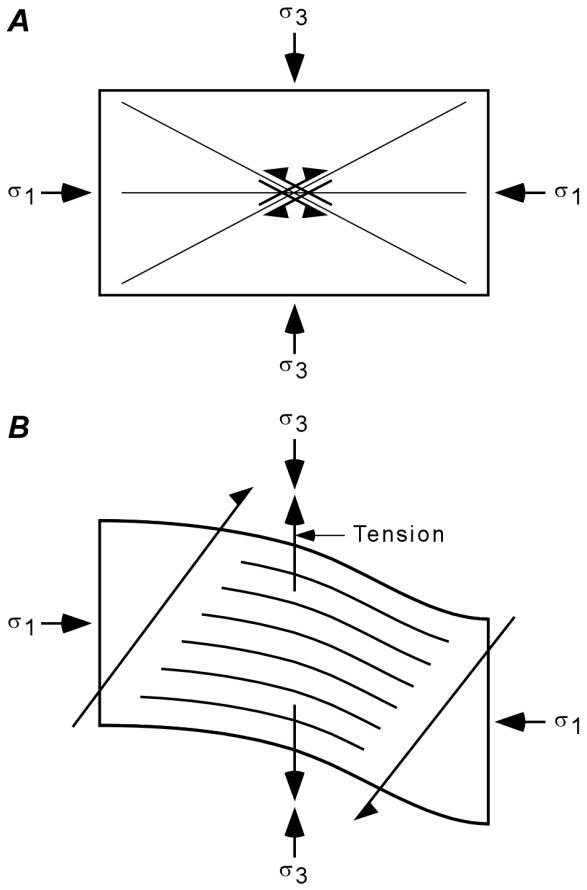


Figure 6. Contrasting views of fracture formation. *A*, Conventional view that principal stresses cause either conjugate faults or extension fractures parallel to greatest principal stress (σ1) through compressive stress alone. *B*, Alternative view as expressed in this paper, that extension fractures, the most common mining-induced fracture type seen in hard-rock mines, result from elastic shearing displacement that generates tension approximately parallel to the direction of least stress. (Note: Distortion is highly exaggerated.)

same strains would create en echelon fractures and a fracture zone with a geometry similar to that of a kink band. In deep coal mines, this situation is relevant to vertically oriented loads that cause new fractures that cut across bedding.

SHEAR MECHANISM APPLIED TO FAMILIAR FRACTURES IN COAL MINES

Formation of fractures at two locations in coal mines can be partially or entirely accounted for by the shear mechanism described above. In examples described here, it is important to bear in mind that fractures are likely to exploit preexisting flaws such as bedding, cleats, and joints. Hence, mining-activated preexisting structures may not be readily distinguishable from inactive flaws. However, the geometries of activated structures are likely to be as illustrated in the examples.

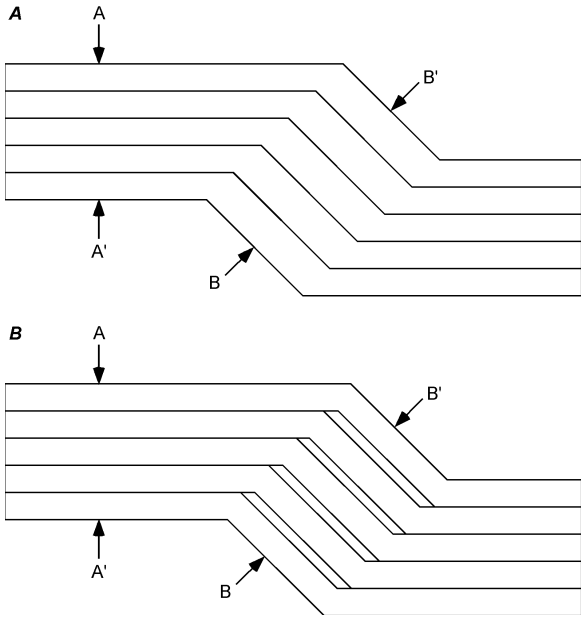


Figure 7. Representation of kink band, a familiar geologic structure. *A*, Dimension B-B' is increased with relative to original thickness A-A'. *B*, Geometry of deformation reduces high interlayer friction by separating layers within band, thus enabling deformation to take place.

Example 1: Face Fractures and Subsidence

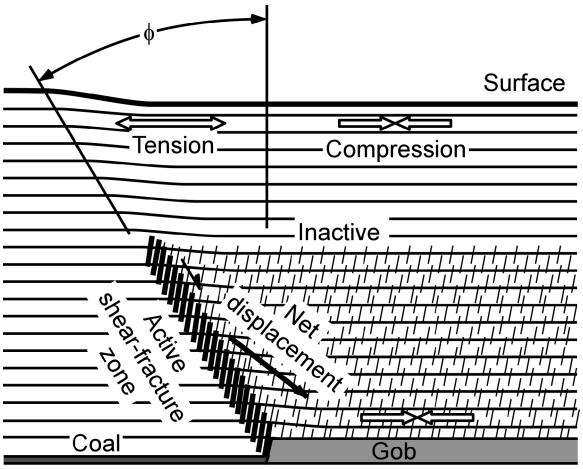
A familiar fracture type seen in longwall coal mines, as well as in South African longwall gold mines and Idaho silver mines, is one that forms parallel to the face. This type is instrumental to cave development (figure 8). These fractures apparently form in the region of high, nearly vertical stress that is concentrated ahead of the face (figure 8*B*).

Longwall mines are also characterized by subsidence that extends beyond the face a distance partially defined by the draw angle φ (figure 8*B*). In addition, horizontal stress changes associated with subsidence increase compressive stress over the longwall panel and create tension adjacent to the edge of the draw (*4*).

The opportunities for shear as a result of the high vertical stress near the face are limited. A direction describing gravitationally assisted movement toward the gob is strongly favored. Thus, a preferred direction of shearing extends upward along the angle of draw. As the face advances, the fractures are pressed closed along the upper edge of the active shear zone and opened below.

This is not the only mechanism likely to be involved with subsidence. Cantilevering may also be a factor, and multiple shear zones may form and extend below the seam, mirroring the zone or zones along the draw line. However, if fractures are well developed at the face, their origin by shearing is likely. Also, if cleats and joints are present and suitably oriented, they will promote this type of deformation.

A



B

Figure 8. Mining-induced fractures parallel to the face in longwall mines. *A*, Hard-rock mine, vertical vein (photo rotated 90° to approximate geometry of flat-dipping coal); *B*, proposed origin of fractures in coal mines as result of shear displacement along angle of draw.

Example 2: Entry Roof Fracture Zone

A second example of familiar mining-induced fractures in coal mines involves those that form parallel to bedding in entry roofs. One example has already been mentioned earlier, in which fracture zones inclined upward from both sides are associated with inverted-V-type roof failures (figure 3*D*). Inverted-V fracture zones obviously require equal horizontal stresses at each corner (figure 9*A*). But, if the major principal stress is inclined with respect to the opening, one corner is shielded from this stress. Fractures will only develop preferentially from the opposite corener and may also extend higher above the back along a steeper plane (figure 9*B*). An inverted mirror image of this zone may also form in the floor (figure 9*B*), but this paper only considers the roof.

Because the coal ahead of the face provides some support, fracture zone development is suppressed at the face. This is an important point.

Both of these situations can by illustrated in plan view (figure 9*C, D*). The fractures and fracture zones are fully developed some distance from the face, while fractures near the face are limited. As a practical concern, rock bolts installed away from the face are inserted through already fractured, sheared, and dilated ground. These bolts are doing the job they do best: They are subjected to tensile load and experiencing only minimal stress, so the roof is likely to be stable providing anchorage is adequate. But bolts installed close to the face in unfractured ground will be subjected to shearing and dilation as soon as the face advances and the fracture zone progresses.

A good example of progressive bolt loading that can be accounted for by this mechanism has been documented by Signer and Lewis (4) (figure 10). Instrumented bolts installed in the roof near the face recorded a buildup of load that progressed downward from high on one side of the roof. Ultimately, loads exceeded the capacity of the bolts, which failed progressively (deepest failure first) until a cave resulted.

These examples suggest that it may be useful to be aware of what kind of fracture zone is forming in the roof and that an understanding of fracture zone geometry and process may lead to more effective roof bolting practices.

SUMMARY

Observations made in hard-rock mines were the stimulus for developing a hypothesis concerning the origin of mining-induced fractures and fracture zones as a product of elastic shear displacement toward mine openings. It is suggested that this explanation for mining-induced fractures may have general application. Thus, lessons learned in hard-rock mines also apply to fractures and bedding plane separations in coal mines. Understanding the mechanics of fractures and their fracture zones can lead to more effective mining and ground control methodologies.

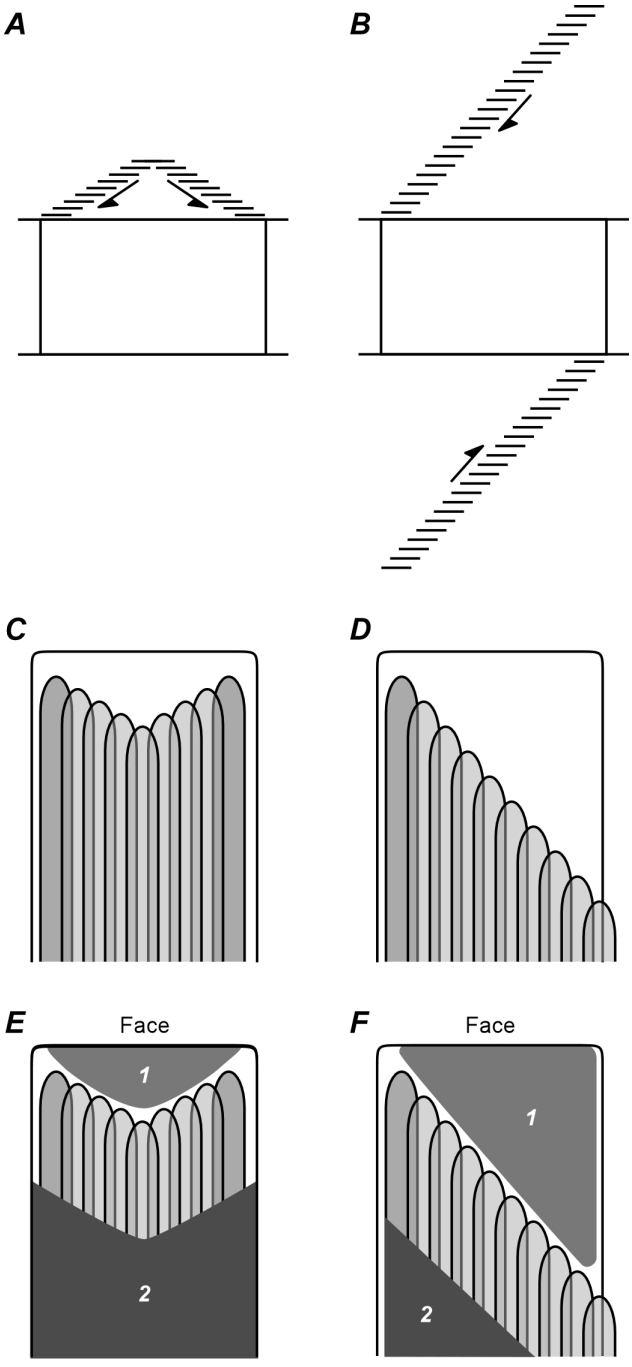


Figure 9. Fracture zones in entry roofs. *A*, Horizontal stress produces symmetrical fracture zones. *B*, High subhorizontal stress generates asymmetrical fracture zones that are steeper and extend deeper than fracture zones shown in A. *C*, Plan view of *A* in which fractures are viewed through roof. *D*, Plan view showing fractures in *B*. *E, F,* Roof bolts installed in area 1 are subjected to dilation and shearing as fracture zone follows face advance; bolts installed in area 2 are in ground where fracture zone is already well developed.

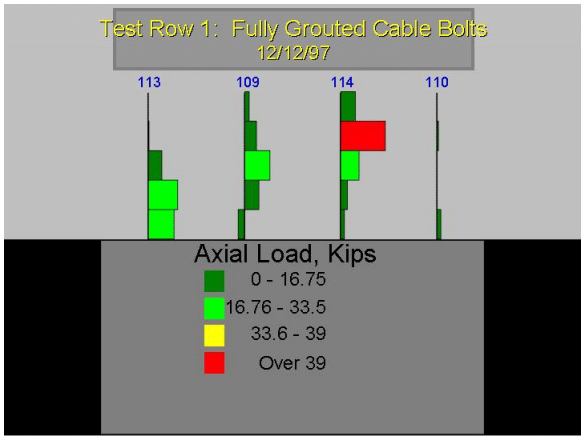


Figure 10. Cross section through instrumented roof bolts installed near entry face (after *5*). Bolts loaded rapidly along a sloping line with subsequent entry advance. Bolt failures progressed downward to the left until total collapse.

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