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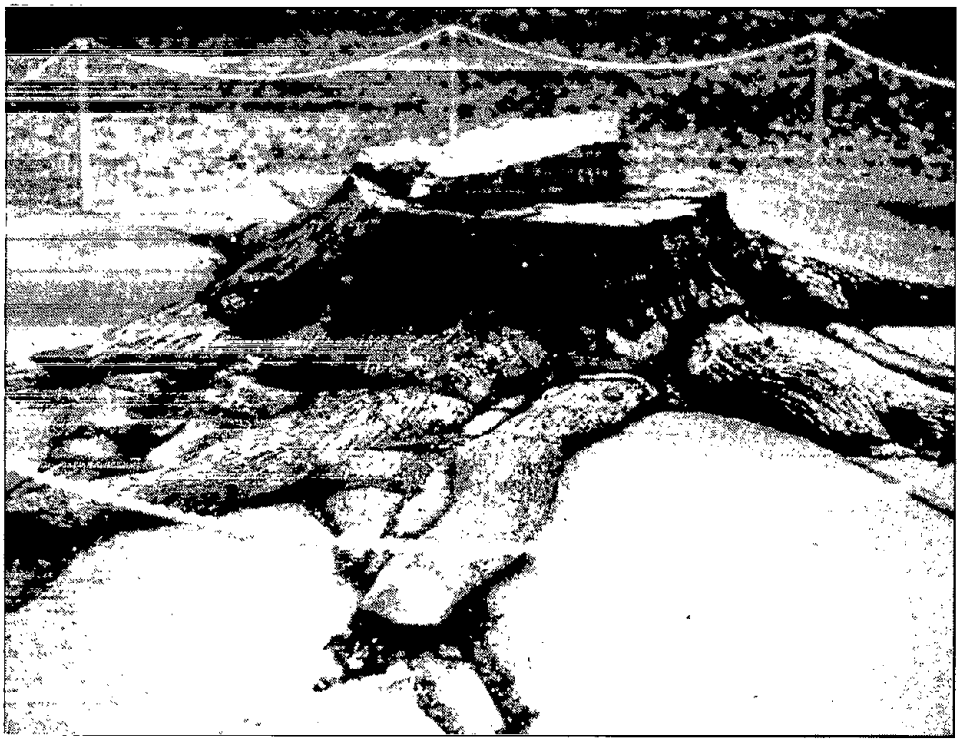
PB94-112299

Geological Features That Contribute to Ground Control Problems in Underground Coal Mines

By Valois R. Shea-Albin



United States Department of the Interior

Bureau of Mines

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Cover Photograph: Fossilized root system of an ancient tree was removed from roof strata of an underground coal mine.

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By Valois R. Shea-Albin

UNITED STATES DEPARTMENT OF THE INTERIOR
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m	meter
d	day	min	minute
km	kilometer	pct	percent
km^2	square kilometer		

GEOLOGICAL FEATURES THAT CONTRIBUTE TO GROUND CONTROL PROBLEMS IN UNDERGROUND COAL MINES

By Valois R. Shea-Albin[1]

ABSTRACT

Ground control problems are an important factor affecting safety, production, and efficiency in underground coal mines. A major portion of ground control problems encountered in underground coal mines can be attributed to geologic features in the strata surrounding the extracted coal seam. The U.S. Bureau of Mines has compiled information from numerous sources on the geological features that contribute to ground control problems in underground coal mines. The compilation includes (1) sedimentary features such as paleochannels, crevasse splays, clastic dikes, mold-and-cast structures, concretions, and lithologic factors, and (2) structural features such as folds, fractures, joints, cleat, and faults. The compiled information will aid in identifying the features, predicting their occurrence in advance of mining, and controlling or minimizing roof failure when these features are encountered in an underground coal mine.

[1]Materials engineer, Denver Research Center, U.S. Bureau of Mines, Denver, CO.

INTRODUCTION

Controlling ground stability problems is a major factor in maintaining safety, production, and efficiency of underground coal mining. Many of the ground control problems encountered in underground coal mines can be attributed to geologic features that occur in the roof and floor of the coal seam being extracted. Some of the features are of sedimentary origin, such as paleochannels, crevasse splays, clastic dikes, mold-and-cast structures, concretions, and lithologic factors; others are of tectonic origin, including folds, fractures, joints, cleat, and faults. Knowledge of the geologic features that contribute to ground control problems can aid in designing a mine layout, roof control plan, and production scheme and help minimize negative impacts to production. Useful knowledge of these geologic features includes familiarity with the geologic processes that formed the features, because understanding their origin helps to identify and predict their occurrence. Information has been published on these features individually and collectively for many years; this information has been compiled in this report to present a comprehensive description of each of these features and its origins. Techniques for predicting the occurrence of each feature in advance of mining and suggestions for solving ground control problems it could cause in the underground coal mine environment are included.

BACKGROUND

The geology of a coal basin is a record of the sedimentary and tectonic history of the area. Sedimentary and tectonic events can be closely related, as with a subsiding sedimentary basin that continually maintains a shallow-water depositional environment through the interaction of fluvial and oceanic processes as recorded by the stratigraphy. Sedimentation and the action of tectonic forces may have been separate in time, as in the case of originally flat-lying strata being deformed by later tectonic events. Both the sedimentary and tectonic features can create anomalies, such as discontinuities or weakness in the strata, that contribute to instability in the underground mining environment.

Although coal seams may be laterally continuous over large areas, coal-related strata frequently vary laterally and vertically over short distances. Such variations reflect the variety of sedimentary processes that existed in the coal-forming environment. Some processes, such as flood events, were sporadic; others, such as meandering river channels, were continuous but migrated in position over time. As a result, the stratigraphy of the coal-forming environment is complex. Such variations in lithology over short horizontal distances present problems when they occur in the roof of an underground coal mine. The changes in roof lithology often cause significant changes in roof stability.

Tectonic events, such as mountain-building processes and basin subsidence, create structural features that disrupt strata continuity. Structures such as folds, faults, joints, and fractures are potentially disruptive features in the mine environment. They introduce weakness in overburden and floor strata that contributes to roof instability.

For the most part the features discussed in this paper may occur in any underground coal mine in the United States, because the environments of deposition in all coal-forming basins were similar. There are differences between the coal basins in the Eastern and Western United States; these differences are the result of time of basin formation and the duration and intensity of the geologic processes that created them. These differences are addressed in the discussion for each geologic feature.

SEDIMENTARY FEATURES

PALEOCHANNELS

Definition and Description

A paleochannel is a laterally discontinuous lithologic unit consisting of younger or contemporaneous sediments that have intersected underlying or adjacent sediments by the erosional action of an ancient stream. The shape of the deposit resembles a stream channel in that it is lenticular, either U- or V-shaped in cross section, and sinuous along its length. Paleochannels are encountered in underground coal mines where they cut into roof strata, and often into the coalbed, truncating original bedding planes (*1-4*).[2] The typical paleochannel-fill deposit is a sandstone composed of closely packed, well-rounded to

[2]Italic numbers in parentheses refer to items in the list of references preceding the glossary at the end of this report.

subrounded quartz grains; therefore, paleochannels are often called sandstone channels. Channel-fill sediments can range from sandstones to siltstones to interbedded sandstones and siltstones. The sandstones can range from clean and well cemented to highly carbonaceous, poorly cemented, and friable. The siltstones may be dark gray because of a high content of organic material but may contain light sandstone streaks (*3*).

A washout is a channel that has partly or totally cut through the coalbed (*5*). Paleochannels are also called wants, rolls, or horse bellies, because the base of the channel-fill sandstone has a characteristic convex downward and sometimes undulating shape (*6*). Figure 1 shows a characteristic paleochannel configuration with a lenticular sandstone cutting down through underlying strata.

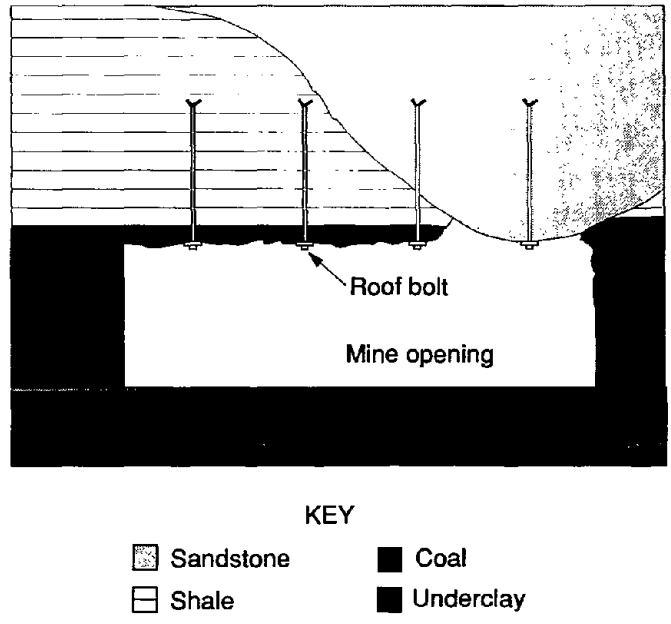

Figure 1.—Typical paleochannel observed in cross section in roof of underground coal mine. Note that channel cuts downward through coal overburden, creating unstable roof conditions, as evidenced by the fallen shale and head coal beneath channel.

Sedimentary Environment

Paleochannels were products of the fluviodeltaic regime, which was also conducive to the formation of coal swamps along the banks of the channel system (*7*). Characteristics of this environment were a flat coastal plain where the channel flow rate decreased owing to the loss of gradient. The meandering river channel showed a high degree of curvature and tended to migrate over time. As the river channel migrated, it created a discontinuous pattern of sediment deposition both laterally and vertically. The coarser grained sediments of the faster moving channel flow migrated over the finer grained overbank deposits, or scoured them away. At flood stage the volume of water exceeded the capacity of existing channels. The increased velocity of the flood currents scoured new channels into adjacent peat deposits in the surrounding swamp or into adjacent finer grained overbank deposits deposited earlier by receding flood waters (*7-8*). In the case of the meandering river migrating laterally over previously deposited peat, the channel currents scoured downward through intervening flank deposits to the underlying coalbed.

The paleochannel penetrated the coal seam by one of three possible methods: compression into underlying strata, contemporaneous deposition, or erosion of underlying strata. In the first case, a younger channel deposit overlying the coal seam was pressed into the older sediments by the weight of overburden. Under stress, peat (which later became coal) migrated to either side of the channel, creating zones of increased coal thickness along the channel margin. In the second case, the channel fill was deposited contemporaneously in an existing streambed lying adjacent to the peat rather than being compressed into the peat. In this case, the coal does not increase in thickness as it approaches the channel, and it may have a clay or shale parting formed by sediments deposited by currents overflowing the channel. In the third case, a channel was cut into adjacent peat deposits at flood stage by high, fast-moving currents that overflowed the main stream channel. This type of channel is active only temporarily during the flood event[3] (*3, 9*). It is abandoned as the flood waters recede, and the sediment load is deposited rapidly without further sorting of grain sizes or winnowing away of lighter material. A number of depositional features characteristic of rapid abandonment may be present in the sedimentary sequence of such paleochannels. A channel-lag deposit within the channel-fill sediment, evidence of stream erosion that occurred during channel formation, may be left in place at the base of the channel. Channel lags usually consist of pebbles and cobbles that were fragments of surrounding strata ripped up by eroding currents. Channel lags may also contain coal streaks or coalified fossils that were probably portions of the peat bog scoured by channel flow (*3*). Load casts, which are irregular bulges formed by rapid deposition of sand on mud, may be present on the underside of the paleochannel (*10*).

The hardness and the dense packing of the quartz grains that comprise the coarser channel sediments resisted volume decrease when subjected to compression

[3]Ingram, D. K. (BuMines Pittsburgh Research Center, Pittsburgh, PA). Private communication, 1993; available upon request from V. Shea-Albin, BuMines, Denver, CO.

from the load of overburden. The lithologic units surrounding the paleochannel were usually finer grained sediments with a high clay content, such as shales and claystones. In response to compression, these sediments experienced realignment of the platy clay minerals, loss of pore space, and expulsion of interstitial water, resulting in a large reduction in volume. Where a sandstone paleochannel occurred adjacent to a fine-grained deposit, the more compactible fine-grained sediments yielded to the sandstone by squeezing out on either side as the sandstone was compressed into them. This situation illustrates a process known as differential compaction (*6*).

Associated Features

Differential compaction occurs when a noncompactible, rigid lithologic unit lies in contact with a more plastic, compactible unit. When the two units are subjected to overburden load, their physical response differs according to their individual compactibilities. The amount of volume reduction depends on depth of burial and the compactibility of the affected sediments, which is related to the amount of pore space available for closure present in the material (*3*). For example, when a sandstone lens is surrounded by shales, the softer shale units are stretched and bent around the rigid sandstone. The unyielding sandstone is pressed into the surrounding shales, which extend laterally around the channel, deforming in a tensional manner (*11*).

The effects of differential compaction upon more compressible lithologic units were more severe near the channel-fill margins and dissipated outward from that boundary. The stresses associated with differential compaction were greatest where a sandstone lens terminated abruptly in a shale or mudstone. The shale adjacent to the lens was contorted and fractured. This pattern of deformation may persist in wide bands parallel to the channel margins. When sandstone was in gradational contact with a shale, there is usually less evidence of distortion of the different lithologic units. Because the compactibility changed gradually with the lithologic variation, the juxtaposition of two materials with very different compactibilities was avoided (*11*).

A number of associated features formed as a result of the differential compaction that occurred around paleochannels. These features include slickensides or slip planes, nontectonic faults, clastic dikes, and clay-dike faults (*3*). Slickensides are curved surfaces that are grooved and striated but otherwise polished smooth by relative movement across the slickenside surface (*12-13*). This relative movement was not of tectonic origin, but was caused by differential compaction of surrounding unconsolidated sediments of different lithology and compactibility. When compression occurs during burial and lithification, the two sediments compacting at different rates will produce shear movement near their interface. Slickensides are evidence of the relative movement (*14-16*).

Slickensides commonly occur in roof rock composed of shale or claystone. Figure 2 shows slickensides pervading overburden strata. When slickensides intersect in the roof, they can isolate wedges or slabs of rock, called horsebacks, that fall free from the roof (*17*). Figure 3 shows the striated face of a slickenside that was exposed after such a fall.

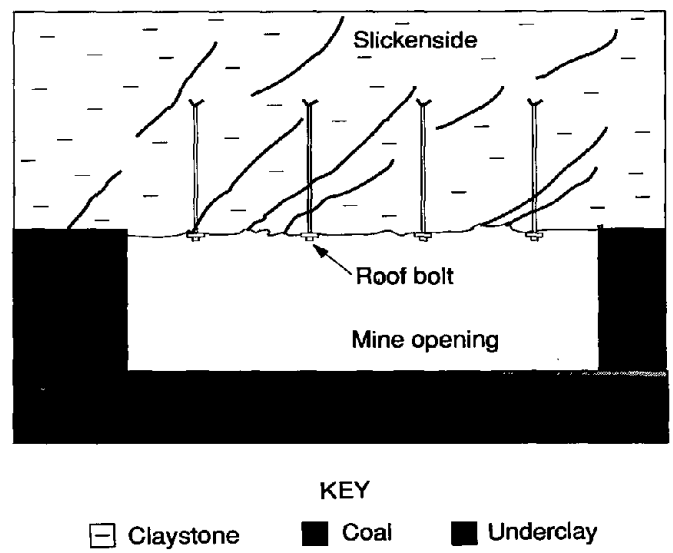

Figure 2.—Slickensides observed in cross section within coal mine roof.

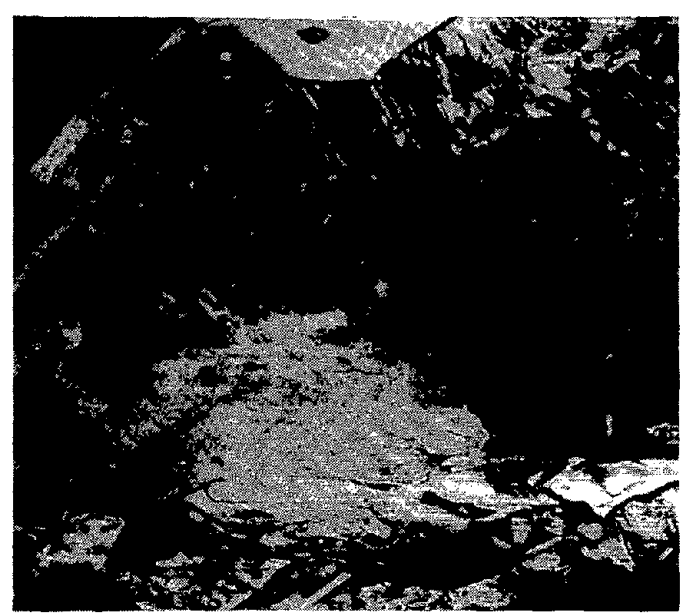

Figure 3.—Slickenside plane showing striations formed by movement along the plane exposed by a roof fall.

Nontectonic faults are fractures formed by forces other than tectonic stresses along which relative displacement or offset has occurred parallel to the fracture plane. They are formed by differential compaction of unconsolidated sediments or by the sliding of large slump blocks. Faults of this type show evidence of soft-sediment deformation by being adjacent to contorted bedding or a displaced slump block and by being truncated suddenly. They formed to relieve stress in the sediment pile caused by the compaction that sediments are subject to as they are lithified. Nontectonic faults are distinguished from tectonic faults by the fact that they do not occur in systems that can be traced continuously vertically or across large areas. Nontectonic faults are not consistently oriented in a preferred direction relative to regional deformational features (*18*).

It has been suggested that clay veins are often associated with paleochannels and occur along their marginal zones. Clay veins and associated clay-dike faults tend to occur parallel, but may be perpendicular, to the paleochannel trend (*3, 19*). These features are discussed in more detail in the section on clay veins.

Features associated with the paleochannel that were formed by depositional processes related to those that formed the paleochannel include paleoslumps, overbank and levee deposits, and crevasse splays. Paleoslumps are remnants of soft-sediment deformation that formed either by differential compaction or when steep channel banks accumulated a sediment load that eventually became unstable and slid down into the deeper portions of the channel under the influence of gravity. An example of a slump formed by differential compaction would be distorted bedding caused by the migration of clays that were more water saturated or more plastic than overlying sediments and flowed laterally under the pressure of overburden intruding adjacent sediments. A paleoslump can range from a rotated block in which the original bedding is intact but appears oversteepened and laterally displaced to an area of chaotic sediments in which the bedding is convoluted, overturned, or completely destroyed by slumping. The variation between undisturbed strata and highly contorted strata can occur within the same slump feature (*20*).

Slump features are usually preserved adjacent to or at the base of the paleochannel because they came to rest in deep channels below the erosional base of the channel currents. These deep channels and rapid, unstable sediment loading may have been caused by a sudden and intense storm event like those that often occur today in tropical to subtropical climates, which are similar to the climate in which coal-forming basins formed (*20*).

The grain size of sediments involved in a paleoslump can range from sand to clay. Sand may have been deposited rapidly on top of mud, causing the sediment pile to become unstable so that the sand slumped downward, while the mud moved outward and upward to displace the sand (*18*). A slump in which sand slumped against shale is easier to detect visually, because of the contrast of grain size, than one where only fine-grained sediments are involved (*20*).

Bedding of sandstone, siltstone, or shale that is rotated, oversteepened, or deformed relative to the surrounding bedding planes would signal the existence of a paleoslump (*20*). Such dislocated or detached blocks of sediment may also be surrounded by shear or glide planes, slickensides, or nontectonic faults formed by sliding of soft sediments (*18*). Slump features can vary in size, involving a large portion of the channel bank deposits and even the surrounding peat deposits, as evidenced by contorted interfingering of sandstone, siltstone, and coal. Continued burial and compaction further deformed and displaced the already distorted paleoslump features (*3*).

Overbank and levee deposits occurred along the paleochannel margin. Levee deposits were natural sediment buttresses deposited along the channel banks by currents of an earlier flood stage. During flood stage, current from the main paleochannel flowed out over the adjacent flood plains. As the currents moved farther away from the main channel, their force dissipated. This decrease in velocity caused the sediment-laden currents to deposit their load over the surrounding plains. A greater volume of sediments, comprising larger sized particles, settled out first near the flanks of the river channel, while a decreasing amount of sediment consisting of smaller particles was carried farther. As a result, the levee and other overbank deposits have a wedge-shaped configuration, thinning and showing decreasing grain size in the compositional sediments away from the river channel. As the flood waters receded, they lost energy, and finer grained sediments were deposited on the coarser grained sediments directly adjacent to the channel banks. This event created a pattern of graded bedding with grain size fining upward within the overbank deposit (*7-8*).

Crevasse splays are discussed in the section on crevasse splays.

Effects on Mining

The presence of a paleochannel in a coal mine roof usually causes ground control problems and interruption of the mining sequence. It is often associated with thinning or complete removal of the coal seam, reducing recoverable reserves and disrupting the mining routine (*3*). Paleochannels and associated features also cause unstable roof conditions all along their trend because disruption of lateral continuity of the roof rocks contributes to roof failures, resulting in costly cleanups, production losses, injuries, and fatalities (*13*). The margins of the channel deposit are usually separated from surrounding strata by

the slickensided interfaces formed by differential compaction. Such slickensided interfaces cause adjacent and underlying beds in the roof to separate and fall after the coal is extracted (*4*).

The distortion of surrounding sediments further contributed to disruption of lateral continuity. Multiple slickensides caused by differential compaction in the surrounding roof create planes of weakness within a unit and between lithologic units by interrupting the physical continuity (*12, 17*). Intersecting slickensides, or horsebacks, usually fall out upon mining, but those undetected ones that do not fail immediately will likely cause problems when subjected to abutment stresses during the pillaring phase in a room-and-pillar mine or when the face approaches in a longwall mine (*17*). Slip planes and nontectonic faults cause the roof to be segmented into cantilever beams (*3*). The features that cause instability along the margins of the channel occur in a zone known as the transition zone that runs parallel to the channel margins and ranges in width from a few meters to as great as 150 m. The width of the transition zone depends on the abruptness with which the channel-fill sandstone wedges out into the surrounding sediment (*11, 14, 17*).

Slump features are unstable zones within the roof rock. Associated discontinuities range from rotated blocks on a large scale to distorted, fractured, and slickensided bedding on a smaller scale (*11, 21-23*). The rotated blocks may be surrounded by extensive shear zones. The disturbed bedding provides a poor roof bolt anchorage zone that would not be detected until a roof fall occurred, exposing the characteristic slump features.

Abrupt termination of surrounding lithologic units against the sandstone channel fill creates a discontinuity that reduces the competence of the roof strata, causes sagging of the units, and leads to roof falls (*14, 24*). Figure 1 depicts a section of roof where incompetent shale and head coal fell beneath the paleochannel. A channel system that consists of narrow multibranching channels causes greater lateral discontinuity and thus increases chances for roof instability (*4, 6*).

Shale-filled channels, like sand channels, have the potential to create stability problems, though the lithology and compactibility of the channel fill may be similar to those of the surrounding material (*25*). Instability originates from the discontinuity of the strata eroded by the paleostream. Differential compaction may still be a factor to the extent that the older surrounding sediments have already been subjected to a certain amount of compaction prior to the deposition of the channel-fill sediments. As a result, there is some disparity between the compactibilities of the channel deposit and the surrounding sediments.

Overbank and levee deposits are inherently weak sedimentary configurations that are located along the paleochannel margin. Levees are often penetrated by roots that interrupt bedding and reduce the strength of the resulting rock (*23*). Overbank deposits include thinly bedded sandstones, sometimes interbedded with shales or claystones. This configuration is prone to separation along the bedding planes, causing roof falls that can encompass a great thickness of overburden. Overbank deposits produce a great potential hazard when their thickness is not known. If the roof bolts are not long enough to penetrate the entire thickness of the deposit and anchor in a more competent stratum, then failure of the whole bolted sequence can result (*6*).

The channel-fill sandstone itself generally forms a stable roof, especially when in direct contact with the coal seam. These sandstones are usually massive, and the lack of thin beds prevents the unit from being prone to delamination (*6*). However, a channel sandstone often consists of crossbeds, shale partings, or coalified fossils, which are planes of weakness that can lead to failure. The massive sandstones are prone to jointing or fracture from brittle response to a buildup of stress. Blocks of sandstone isolated by joint planes can rotate and disrupt the original stress distribution, creating a potential for failure. Fractures caused by brittle behavior of sandstone create zones of weakness. The strength of the sandstone deposit can cause stress distribution problems in the roof. Bumps resulting from stress accumulation in a massive sandstone that will not cave behind the shields during longwall mining or pillaring in a room-and-pillar mine have been documented in as little as 61 m of overburden (*17*). The strength of the rock is directly related to extent, spacing, and orientation of joint planes or fractures (*26*). The lower portions of sand channels often contain coalified logs and pebble lags that were carried as bed loads (*23*). These features tend to create weak zones in the otherwise competent sandstone unit (*4*).

Because sandstones are often aquifers, a sand channel in the immediate roof can be a source of water flowing into the mine workings, especially if intersected by roof bolts. The presence of water lubricates preexisting planes of weakness, such as slickensides, joints, and fractures. Inflowing water can contribute to weathering of the roof shales and cause them to slake, thereby decreasing their competence. Water collecting in the workings will eventually require pumping, especially if mining is advancing down dip and water is collecting at the face or along major haulageways. Resin bolting may be necessary to stop the water flow through roof bolt holes (*23*).

Some investigators believe that in Western U.S. coalfields unstable roof conditions are attributed to paleochannels more often than to any other geological feature. Rapid erosion of the newly uplifted orogenic highlands created a large sediment load carried by river and stream channels flowing rapidly down steep gradients into rapidly subsiding basins. Flood events were frequent and of high volume, creating numerous complex paleochannel systems (*4*).

Recommendations for Roof Support

Critical areas for roof support are the transition zones along the channel margins, which often require a more stringent roof support plan. Because this marginal area is so weak, it is important to install roof support as soon after mining as possible to prevent or reduce spalling of immediate roof layers. Longer or angled bolts may be required to reach stable strata to provide adequate anchorage to support the weaker immediate roof. Closely observing the angle of dip of the slickensides located along the paleochannel margins can help determine if angled bolting is necessary and the drilling angle that would be effective in supporting the roof along the channel margins. If longer bolts installed at an angle can anchor into a strong channel sandstone, they would provide support to the weak rocks of the immediate margin. Tensioned bolts, such as tensioned point-anchor resin bolts, should help to compress disturbed and fragmented roof within the marginal zone. Often bolts alone, even though anchored in a stable zone, cannot prevent spalling of weak roof between bolts. Supplemental support, such as steel straps, crossbars, and wire mesh, can be used to reinforce the immediate roof between bolts. Unstable roof associated with larger, more hazardous paleochannels may require steel sets, cribbing, or roof trusses (*3-4, 13, 17*).

Predictive Techniques

Detecting the presence of paleochannels on a coal mine property prior to mining is difficult. Because paleochannels are long but narrow features, they may be difficult to detect through exploratory drilling on widely spaced centers. If a drill site intersects a thick, crossbedded or massive sandstone near the top of the coal, but an adjacent drill site lacks such a sandstone, the presence of a paleochannel may be inferred. More extensive drilling, supplemented with careful underground mapping, will help determine the trend of the channel (*1, 3, 12, 19*). 'Developing isopach maps and fence diagrams from drill logs and underground mapping aids in predicting trends of paleochannels and projecting them into unmined areas (*27-28*). Thinning or disappearance of the coal seam beneath the channel should be detectable using geophysical methods, such as propagating channel waves along the coal seam from outcrops or from exposures underground, such as the working face or the excavated boundaries of a longwall panel (*3*). Some success has been reported in mapping paleochannels with satellite imagery, but field checking and mapping of existing mine workings are necessary to verify that the features are paleochannels. Once a lineament has been verified in the field to be a paleochannel, the feature can be projected into unmined areas with confidence, based on the trend of the lineament (*29*).

A number of investigators have noted phenomena that, when encountered during mining, may indicate that the entry is approaching a paleochannel (*1, 14, 30-31*). A thickening of the coal seam toward the channel, from the resistant sandstone channel fill being compressed into the more compactible coal seam, is one indicative feature. As a result of this same process, partings within the coal may appear to be down bowed adjacent to the channel margins.

There may be an increase in the number and thickness of partings in the coal toward the channel as well as an increase in the detrital particle content in the coal. In some cases, a parting may become so thick as to create a split in the coal seam. These features are a result of the channel waters overflowing the channel and depositing fine-grained sediments beyond the channel banks in the coal-forming swamp. The sulfur content in the sediments immediately surrounding the channel may increase as a result of the leaching of pyrite from the more permeable channel sands. Sulfur content can be analyzed from drill core and noted on the mine map to indicate that a change in roof conditions may occur (*4, 32*). A rise in floor elevation toward a channel may result from the natural levees flanking the stream channel. The bedding planes of shale and other sediments surrounding the channel may be disrupted by differential compaction. Because the surrounding sediments are usually more compactible than the channel deposit, compression due to burial causes enough deformation to obscure any bedding. Increase in frequency of fractures in the roof is sometimes observed as the paleochannel is approached. The fractures usually occur in a preferred orientation, either perpendicular or parallel to the trend of the channel. The fractures may be filled with gypsum or anhydrite from water seepage and are then called goatsbeards (*4*).

Slump features in roof rock signal the presence of a paleochannel. A slump feature is easily distinguishable in a drill core, indicated by rotated, oversteepened, or deformed bedding, arcuate shear planes, or dislocated or detached blocks of one sediment type surrounded by a different sediment type (*20-21*). Unfortunately, these localized features are intersected by a drill hole only by chance and are usually not distinguished until exposed in a roof fall caused by their presence. Careful roof mapping, noting rapid lateral changes in roof rock, glide planes, and distorted bedding, can be helpful in early recognition of slump features. The occurrence of one fall related to a slump feature should warn of the possibility that other such features may exist (*33*).

It has been suggested that the presence of clay veins can signal the proximity of a paleochannel. Clay veins and associated clay-dike faults tend to occur parallel, but may be perpendicular, to the paleochannel trend (*3, 19*). These features are discussed in more detail in the section on clay veins.

The presence, or an increased amount, of water encountered along the roof, roof bolts, and fractures is another feature indicative of a paleochannel. The sand channel often contains water that accumulates along the bottom of the channel, where it is trapped by an impermeable shale barrier surrounding the channel. Once fractures penetrate the shale, the water is able to escape the channel sand and flow along the fractures to roof bolt holes.

Overbank deposits encountered during mining often contain sedimentary features, such as ripple marks, thinning beds, and graded bedding, that indicate direction of paleocurrent flow. Direction of the paleocurrent can be used to determine the location of the paleochannel. The paleochannel system served as the source for the currents that deposited the overbank deposits during flood stages. Therefore, current flow is oriented at a high angle to the trend of the channel, and direction is away from the location of the channel (*11, 22*).

CREVASSE SPLAY DEPOSITS

Definition and Description

Closely associated with the paleochannel system are crevasse splay deposits, which are usually composed of thin, brittle beds of sandstone of the same composition as the main paleochannel, deposited on finer grained overbank deposits. As shown in figure 4, a crevasse splay is a tongue of sediment that can range from lobate to fan-shaped. It forms a wedge in the cross section as it tapers laterally from the levee flanking a channel toward the adjacent flood plain. The size of a splay deposit can vary depending on the duration that its depositional system was active, the sediment load and velocity of the currents, and the volume of water that passed through the system. Because splay deposition is a brief, sporadic event, the sedimentary units are usually less than 8 km^2 in area and less than 3 m thick. The sediments of a splay deposit generally coarsen toward the paleochannel and contain associated siltstone and mudstone beds. Near the channel margin, the splay sediments usually exhibit a decrease in grain size upward in the unit, reflecting the decrease in current flow energy near the end of the sedimentary event (*34*).

Splay deposits tend to be coarser than the overbank sediments upon which they were deposited. Overbank sediments were usually deposited by receding flood waters, which flowed more slowly, carrying silt- and clay-sized sediments. A crevasse splay was deposited early in the flood event by currents of greater velocity that were capable of transporting larger sediment particles (*8, 12, 25, 34*).

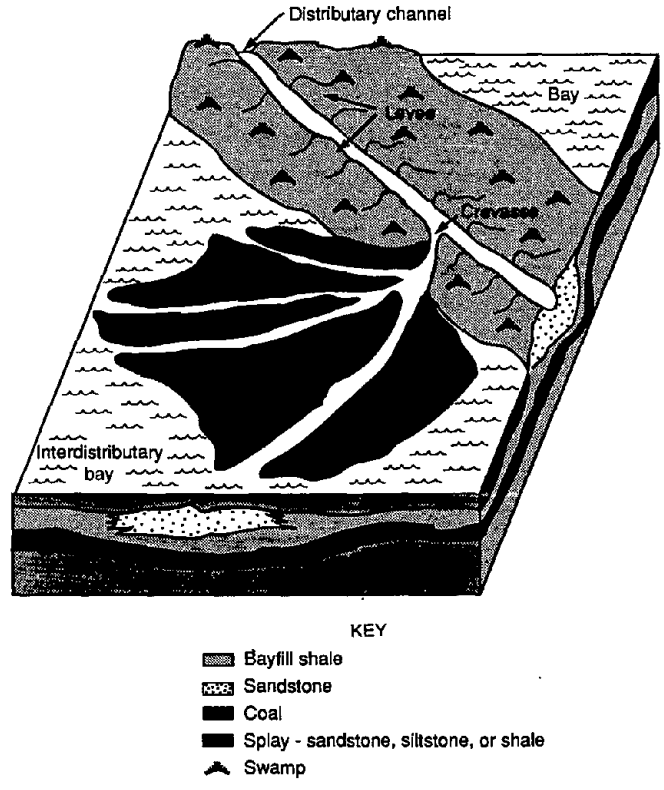

Figure 4.—Crevasse splay deposit and associated features formed by channel currents that breached natural levee of channel at flood stage and deposited their sediment load in a fanlike configuration.

Sedimentary Environment

Like an overbank deposit, a crevasse splay was formed by channel flow at flood stage, when the volume of water flow exceeded the capacity of the channel to contain it within its natural levees. The high-velocity, high-volume river currents overtopped and scoured a channel or crevasse through the levees flanking the paleochannel. Carrying an increased sediment load, the currents flowed out over the surrounding peat bog and overbank deposits. Splay sediments were, therefore, deposited by an active stream that was a minor branch nearly perpendicular to the main channel system, in contrast to the slowly moving water that overflowed the channel banks and created the finer grained overbank deposits. Water diverted from the channel system through this crevasse was turbulent enough to carry sand-sized sediment particles in suspension. As the sediment-bearing stream spread over the adjacent flood plain, the current velocity decreased, allowing the coarser grained sediments to settle. These sediments were

deposited on a substratum scoured by the splay current flow. Because most of the crevasse splay deposits originated from the active channel, they are the major sites of laterally widespread sand deposits. The fine-grained sediments were carried farther than coarse-grained sediments and were deposited in a fan-shaped configuration exhibiting particle size gradation similar to that of a delta (*8, 25, 34*).

Frequently in the delta environment, a crevasse splay encroached upon a peat bog and covered the swamp vegetation with a layer of clastic sediments. Once the flood waters subsided and the deposition of clastics ceased, the swamp environment was reestablished and vegetation covered the splay deposit. Rider coal seams were formed by this process of the swamp environment growing over a splay deposit. The splay deposit overlies the main coal seam and forms the split between the main seam and the rider coal (*34*).

Associated Features

Because crevasse splay deposits are closely associated with paleochannel deposits, they share similar associated features. Splay deposits, comprised mainly of sand, were deposited on the finer grained overbank deposits. This juxtaposition of coarse- and fine-grained sediments led to differential compaction. Because crevasse splays were deposited adjacent to the channel, they were subject to invasion by the migrating channel. In addition, later-forming splays may overlap and cut into preexisting splay deposits. Any of these events contributed further to the discontinuous nature of splay deposits, leading to increased roof instability when they occur above a coal seam.

Some sedimentary features characteristically associated with crevasse splay deposits are small-scale crossbeds, climbing ripple laminations, and horizontal bedding. Scour-and-fill features are occasionally observable, as are large-scale crossbeds. Fossilized plant debris and animal debris are often concentrated in splay deposits (*8*). The small-scale crossbeds are composed of individual beds ranging in size from 0.25 to 5 cm, which are usually trough shaped. Climbing ripple laminations are superimposed laminae built upward rather than offset in a forward direction (*8, 34*). Scour-and-fill structures are small, asymmetrical troughs in the substratum filled with a different sediment type. Large-scale crossbeds are internal bedding structures ranging in thickness from 5 cm to 2 m and are oriented at an angle to horizontal bedding (*8*).

Effects on Mining

Crevasse splay deposits contribute to roof instability when they are encountered as roof rock in underground coal mines. One characteristic of the crevasse splay that causes unstable roof is the inherent weakness of the strata that comprise the deposit. The sandstones tend to be micaceous, thin bedded, and interbedded with siltstone or shale. The presence of thin coal laminae, plant debris, and an abundance of clay in the matrix also contributes to the weakness of the units. The thin, brittle beds are prone to separation along bedding planes or between the sandstones and thin laminae of siltstone or shale, allowing large slabs to fall. Roof falls caused by crevasse splays often occur soon after the removal of the coal, before there is time to install roof bolts. Once the coal has been mined and is no longer present to support the weak units, the thin beds begin to sag, delaminate, and fall. The roof falls tend to be severe, penetrating far into the roof, creating a large dome-shaped cavern that is difficult to rebolt (*4*). Even after roof bolts have been installed, slabs may fall between the bolts. A very hazardous situation occurs when crevasse splay intervals are thicker than the length of the roof bolts. Separation then occurs above the bolted sequence, and large roof falls, up to 3 m in thickness, occur. Falls of this nature are unpredictable, adding further to the hazard (*6*).

Another potential source of instability related to crevasse splay deposits is the discontinuous nature of the units. The internal structure of the deposit consists of interfingering finer and coarser grained sediments caused by variation in current velocity and sediment load. The discontinuous nature of the strata creates zones of weakness in the roof (*21*).

Crevasse splays are a common problem in Western U.S. mines, where they are found in the roof of nearly every coal seam. They are most unstable when they occur 2 to 3 m above the top of the coal seam, above the roof bolt anchorage level. The noncohesive nature of the thin beds causes delamination of the roof, resulting in massive falls. Roofs containing crevasse splay sequences tend to become even less stable as overburden thickness increases and are highly unstable in mines where overburden exceeds 500 m. Instability problems associated with crevasse splays can intensify in intersections (*4*).

Recommendations for Roof Support

Often a crevasse splay occurs some distance into the roof and, like the slump feature, is undetectable until a fall occurs, exposing the characteristic sedimentary sequence. If the presence of the crevasse splay is known from exploratory drilling, longer roof bolts should be used to anchor in a stable zone. Tensioned bolts can hold the thin laminations in compression, forming them into a stronger beam. If the crevasse splay occurs too far into the roof to be spanned by longer bolts, additional support, such as wooden posts, cribbing, or roof trusses, should be installed (*35*).

Predictive Techniques

The presence of a crevasse splay deposit may be inferred from the presence of a thin-bedded sandstone located near a paleochannel in drill logs or in exposed mine roof (*21*). The presence of climbing ripple laminations in association with scour-and-fill features, thin-bedded sandstones, and interbedded shales indicates the possible existence of a crevasse splay. A thickening or an increase in grain size of a lithologic unit toward a channel would suggest that the unit is a crevasse splay. When a crevasse splay is deposited upon a peat bog, it can protect the underlying peat from the action of the sulfur-reducing bacteria that are prevalent in a marine-brackish water environment. The pockets of low-sulfur coal in high-sulfur coal seams in the Eastern U.S. coal basins are attributed to this depositional regime. A pocket of low-sulfur coal within a high-sulfur coal seam may indicate an overlying splay deposit (*34*).

CLASTIC DIKES

Definition and Description

A clastic dike is a tabular body of clastic material that has been injected into a fracture, joint, or other zone of weakness in a coal seam, mine roof, or floor. The clastic material may consist of sandstone, siltstone, clay, or carbonate. Clastic dikes are also referred to as horsebacks, spars, sedimentary dikes, and rock spars; when composed of clay, they can be called clay dikes, clay veins, and clay slips. The width of a dike may range from less than a centimeter to several meters and tends to vary along strike. The vertical extent of penetration may be several meters, intersecting a number of geologic strata. A clastic dike may be traceable along its strike across only one entry, or it may extend for hundreds of meters across several mine entries and up to a kilometer or more. Some dikes split and radiate outward from the main stem of an intrusion, encompassing fragments of host rock or coal, as shown in figure 5[4] (*1, 13, 17, 30, 36-38*).

The degree of lithification of the clastic material varies in different situations. Some clastic dikes are filled with lithified rock mass that is significantly harder than the host rock. Other clastic fills are in a plastic state (*1, 39*). The contact between clay-filled veins and their host rock has been observed to be very jagged, as if the peat bed had been pulled apart and shredded, possibly the effect of differential compaction after intrusion of the clay vein. The clastic fill may contain fragments of the surrounding coal or host rock, formed either by collapse of host rock into a tension crack, after which it was engulfed by the intruding vein fill, or by host rock fragments being pulled from the walls of the crack by the intrusion of the vein fill[5] (*13, 36, 40*).

Method of Formation

The emplacement of clay veins is a postdepositional process that involves two steps that may have occurred simultaneously or separately: (1) formation of the fracture, joint, or zone of weakness, and (2) emplacement of the clastic fill. Some mechanisms suggested for the formation of fractures and zones of weakness include earthquakes, soil creep, desiccation, differential shrinkage of coal-forming material during lithification, tectonic deformation of strata, differential stresses created in strata near areas marginal to sand lenses or other discontinuous strata, differential compaction near a sand channel, and drainage patterns that developed in the coal-forming swamp (*36, 39, 41*).

The immediate and main roofs above a coal seam intersected by clastic dikes are composed of various marine and nonmarine sediments, such as thin, massive, or interbedded limestones, shales, or siltstones. In the East, clastic dikes appear more often in coal-bearing strata deposited in more stable continental basins than in coal basins formed on less stable, rapidly subsiding platforms. More stable basins, with correspondingly lower rates of sedimentary influx, foster the pattern of a prograding sedimentary sequence, creating more lithologic variation both laterally and vertically. More rapidly subsiding basins and a greater sediment volume create a sequence of thicker, more laterally continuous lithologic units. Because clastic dikes tend to be associated with boundaries between rocks of contrasting physical properties, differential compaction is thought to play an important role in their formation (*36*).

The clastic fill of the dikes or veins existed originally at some stratigraphic horizon either above the coal seam or below it. Under pressure, the clastic material migrated from its original position and followed the path of the fracture or zone of weakness through intervening strata and the coal seam. The path of migration may be a single fracture or conduit, or it may consist of multiple, intersecting, branchlike feeders (*17*). The formation of the fractures or zones of weakness preceded the intrusion of the clastic material. The fractures expanded as the clastic material was injected. The zones of weakness responded to the force of the clastic material intruding under pressure by failing and opening as the clastics moved in.

Two contrasting geologic processes may have controlled clastic dike formation, as illustrated in two different Western U.S. coal basins. The distinctive trends of clastic

[4]Hardie, J. K. (U.S. Geol. Survey, Denver, CO). Private communication, 1992; available upon request from V. Shea-Albin, BuMines, Denver, CO.

[5]Work cited in footnote 4.

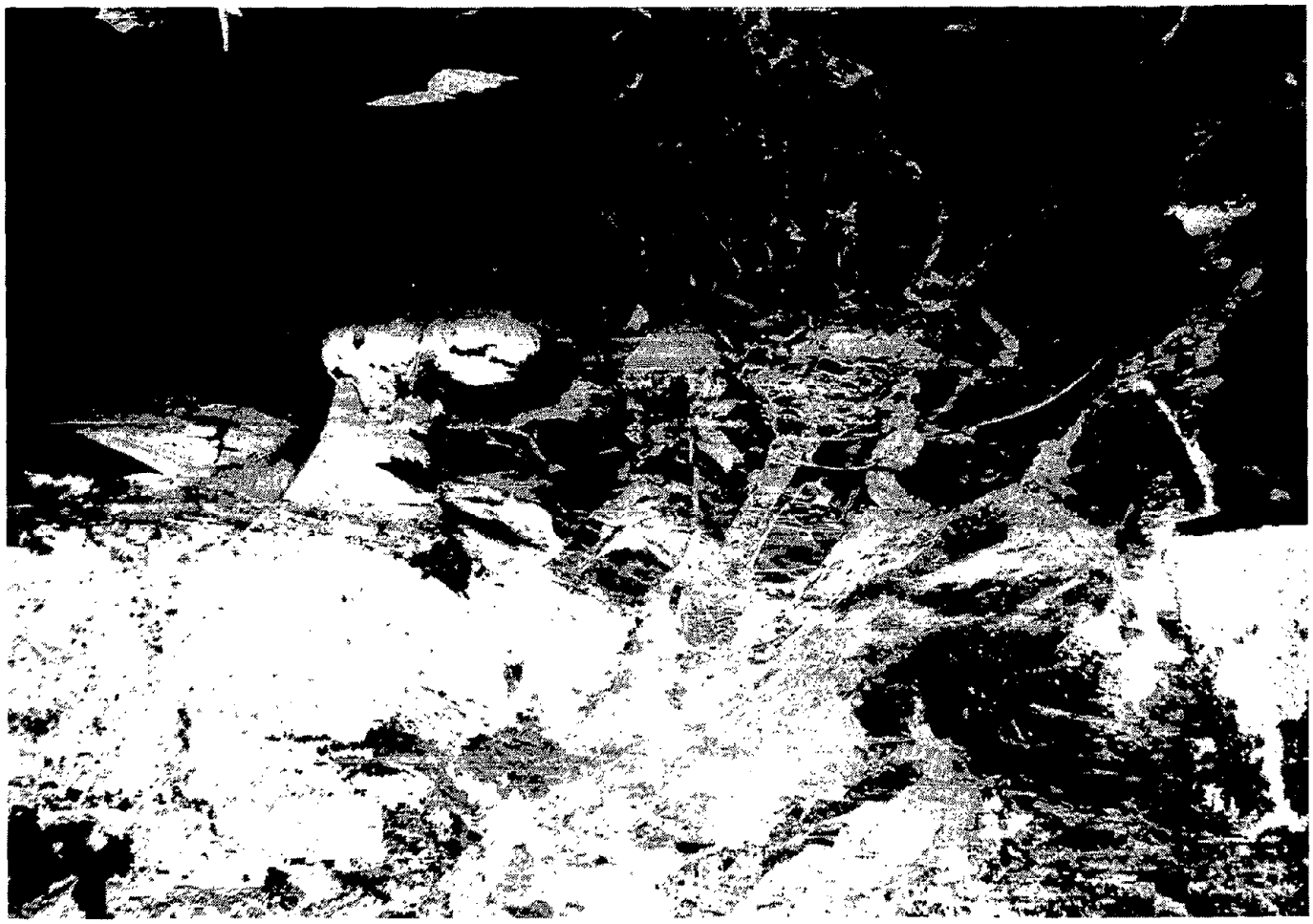

Figure 5.—Clay vein penetrating coal seam and immediate roof stratum in a radiating pattern encompassing fragments of host rock.

dikes in an underground coal mine in the Piceance Basin of western Colorado suggest that tectonic forces influenced their formation. Longer, more continuous sandstone-filled dikes parallel the major axis of regional compression and a joint set thought to be formed as a result of the compressive forces. Shorter, less continuous dikes are coincident with a joint set oriented at high angles to the release joints. This second joint set is thought to have formed by relaxation of the regional compressive forces. The sandstone within the dikes probably originated from an underlying sandstone that was pressure-injected into the joints. The dikes penetrate both the roof and floor rock of the coal seam. In the roof rock, these dikes exhibit a fairly uniform thickness and clean, smooth contacts between the clastic fill and host rock, as seen in the top portion of figure 6. In the coal seam, however, the width is variable and the contact is jagged, but the trend is vertical, paralleling the prevailing joint orientation.[6]

In an underground coal mine located in the Wasatch Plateau coalfield, dolomite dikes were depositionally controlled by the location of dolomite pods located within a basal sandstone. Petrographic studies reveal that the dolomite in the dikes is similar in composition to the dolomite pods intersected by drill cores in the floor. Differential compaction of the water-saturated carbonate pods deposited along the paleoshoreline forced the more compactible pods to flow upward into the coal.

The trend of the major dikes parallels the paleoshoreline. Depositionally controlled dikes are usually pyramidal in shape and terminate within the coal seam before reaching the roof rock. An example of this type of dike is shown in figure 7. Clastic sills injected along the coal bedding are found associated with dikes of this type.[7]

The features surrounding the clastic dikes indicate that the basic mechanisms of formation can be summarized as vertical compression in conjunction with lateral extension

[6]Work cited in footnote 4.

[7]Work cited in footnote 4.

Figure 6.—Joint-controlled clastic dike filled with sandstone intersecting coal seam and roof rock along a joint.

Figure 7.—Depositionally controlled clastic dike filled with dolomite originating from dolomite pods located within sandstone underlying coal seam.

of the coalbed and surrounding strata. During the compaction and diagenesis of the coal-related strata, the volumes of the respective strata decreased at different rates. Within the coal seam itself, differential compaction may have resulted from the nonhomogeneity of coal-forming plants. During the process of diagenesis, a brittle stratum tends to become increasingly resistant to overburden pressure. The pressure builds until the critical stress is reached, and the stratum responds by tensional fracturing. A plastic stratum responds by plastic deformation and flow. When a brittle stratum and a more plastic stratum are adjacent to each other, they adjust to counterbalance the irregularities of their respective deformational features. A combination of the compression due to overburden and reduction in volume of sediments due to dewatering would lead to tensional fracturing or zones of weakness in brittle strata. These zones of incipient weakness or fractures provided a pathway for the plastic sediments to flow away from areas of greater pressure. The fractures enlarge to accommodate the increasing volume of intruding plastic sediments. Slip surfaces formed in the more rigid strata that were being compressed adjacent to plastic strata. Whereas the plastic stratum flowed away from a pressure point, the rigid stratum shifted laterally and was fractured. The plastic material may have even flowed into these fractures and served as a lubricant for additional slippage (*1, 39, 41*). In the case of sand-filled dikes, dewatering of a saturated shale or downward percolation of ground water could have entered a porous, unconsolidated sandbed and entrained the suspended sand particles. The suspended sand would then have been mobile enough to flow into available fissures or to penetrate existing zones of weakness in adjacent strata[8] (*36*).

When a dike terminates within the coal seam and the point of entry can be observed, the clastic material can be traced to its origin either above or below the coal seam. When the dike penetrates the entire thickness of the seam, the source direction is not readily discernible. Further investigation is required to determine the origin of the clastic fill (*38*). Slickensides may help to determine direction of clay movement within the fracture (*37*). A

[8]Work cited in footnote 4.

mineralogical comparison of the clastic dike and surrounding strata can determine the source horizon from which the clastic material migrated. Mineralogically, the clastic fill may contain clay- to silt-sized quartz and feldspar grains, silicic clay minerals such as kaolinite and illite, and occasionally calcareous or dolomitic components[9] (*16, 42*).

The internal structure of clastic dikes has raised questions regarding the mechanics of soft-sediment flow and penetration of fissures. Jenkins (*43*) observed in a great number of clastic dikes a pattern of vertical stratification parallel to the boundaries of the fracture. This stratification pattern appeared frequently even in cases where the clastic dikes were very narrow or branching. He constructed an experimental model with colored, laminated clays under a uniform vertical compression. Responding to the induced compression, the clays entered a crevice that extended beneath them perpendicular to bedding. Even upon flowing into the crevice, the colored laminations were preserved, but they were oriented parallel to the walls of the crevice, perpendicular to the original lamination. This experimental model indicates that clay dikes can be injected under pressure from a clay stratum into fractures at an angle to bedding by means of vertical compressive forces such as would be induced by the weight of overburden. Upon injection of these clays, it is possible for original lamination within the injected clay to be preserved, but reoriented to parallel the walls of the fracture.

Associated Features

Slickensides occur frequently with clastic dikes. Some slickensides are of small extent, existing only within the dike itself. These small slickensides usually occur along planes where slippage occurs between the clastics already filling the dike and newer clastics being injected. Slickensides located within clay veins tend to be oriented parallel to the trend of the clay vein and to dip toward the center of the vein. The angle of dip of the slickensides tends to be steeper (>30°) near the margins of the vein, while dips are more shallow (<30°) nearer the center of the clastic fill (*13*). Slickensides also occur in parallel sets within the host rock surrounding the clastic dike. The parallel sets of slickensides may intersect in a V-shape oriented upward or inverted, with the clastic dike cutting through the middle of the intersecting sets. As the size of the clastic dike increases, the greater the number and extent of slickensides present, thereby widening the disturbed zone surrounding the clastic dike (*36*).

Slickensides also occur as much larger scale features extending beyond the actual clastic dike. On such a scale, they are known as clay-dike or clastic-dike faults (*18, 36, 44*). These features can occur at varying angles to bedding. They may be steeply dipping, resembling normal faults (*36*). More commonly, they have moderate angles of dip between 30° and 35° and curve along the dip, being flatter near the top portion, merging into bedding planes, and becoming steeper to nearly vertical near the bottom (*18*). Clastic dike faults have been known to offset the coal seam as much as 6 m, but usually offset is only 0.5 to 1 m, with maximum offset near contact of coal with roof rock (*18, 36*). Although they may extend laterally up to thousands of meters when mapped in underground coal mines, unlike tectonic faults, clay-dike faults are not linear along the strike but are curved or circular. They may occur in sets or swarms and commonly run parallel to boundaries between rock types with very different physical properties (*18*).

A phenomenon known as false drag exists frequently in association with clastic dikes. False drag occurs when coal layers adjacent to the clastic-dike fault bend upward in the footwall and deflect downward in the hanging wall. This orientation of deformed bedding is opposed to the direction of normal drag and has the effect of increasing the apparent offset along the clastic-dike fault. Although there is no agreement on the causes of false drag, it might indicate that the sediments were deformed during diagenesis before lithification was complete (*18*).

Adjacent to the clastic dikes and associated "faults," the coal seam and roof rock show upward or downward warping extending as much as 2.5 m away. The internal bedding planes of the coal may converge, and en echelon fractures may occur near these points of inflection and convergence. The dip of the coal cleat may change within the warped zone (*36*). In areas where clastic dikes penetrate the entire thickness of the coal seam, the underclay appears to penetrate slightly upward into the coal seam. The presence of these features also indicates penecontemporaneous deformation as the result of compaction (*43*).

In Western U.S. coalfields, clastic dikes often occur in association with paleochannels, where they represent soft-sediment injection into ruptures in the coal during or after coalification. They exhibit a preferred orientation parallel and perpendicular to the trend of the paleochannel (*4*).

Effects on Mining

The presence of clay veins in the roof of a coal mine creates hazardous conditions. When a clastic dike trends parallel or nearly parallel to an entry or crosscut, it divides the roof into one or two beams, depending on the distance from the rib line. If the clastic dike is located toward the center of the opening, the roof is divided into two beams, partly supported by pillars but unsupported in the opening.

[9]Work cited in footnote 4.

If the clastic dike is near the rib line, the effect is that of a long beam unsupported across the entire opening (*36*).

Associated slickensides create zones of loose and fragmented rock that are difficult to support (*36*). Upon exposure to moisture, even the lithified clay dikes tend to slake and fall out of the roof, even after roof support has been installed (*13, 36, 39*). Clay veins are lithologic discontinuities in the roof strata that create zones of weakness that lead to failure (*42*). When the veins extend through several strata in the roof, the effect of a large unsupported beam is created, and a high potential for failure exists. Often two or more clay dikes will intersect in the roof and isolate a large block of unsupported rock, resulting in a particularly serious rock fall once the underlying coal is removed (*36, 44*).

In some mine environments, clastic dikes have been found to contribute to cutter roof failure, especially when a dike intersected the roof near a rib line. Monitoring of rock pressure around the clastic dike confirmed that the greatest amount of roof loading occurred at the intersection of a dike with a rib. Cutter roof failure would begin as a fracture along one or both roof-rib lines of an entry and propagate nearly vertically into the roof. When the fracture penetrated a weak bedding plane above the anchor zone of roof bolts, massive roof failure usually occurred (*40*).

Clastic dikes are often associated with increased methane emissions and infiltration of water. Because clastic dikes are impermeable, their presence inhibits the flow of gas and water through more permeable strata. As a result, a buildup of gas pressure can occur in isolated cells of host rock enclosed by the clastic dikes. The pressurized gas is released upon mining (*1, 9, 13, 45*).

Clastic dikes in the coal seam add to the amount of waste rock to be excavated with the coal, placing an extra burden on the coal preparation facilities (*13*). Mining through clastic dikes of sandstone or siltstone in the coal seam shears mining bits or increases their deterioration, creates greater frictional heat, generates sparks that can ignite the associated additional concentrations of methane, and causes severe vibrations in the already unstable surrounding roof (*13, 36*).

Recommendations for Roof Support

If roof surrounding the clastic dike is not severely disrupted, stabilization may be achieved with only minor changes to the bolting plan. Mechanical bolts may be adequate if they are anchored in stable rock that is undisturbed by the slickensides and other disruptive features associated with the dike. Tensioned bolts help to compress the loose fragments of roof penetrated by slickensides. It is often difficult to determine the boundaries of the disturbed zone surrounding the clastic dike. Excessive bleed-off or inability to maintain the required torque signals that longer bolts are needed to extend farther into the roof and reach a stable zone. Resin anchor bolts may consolidate the fragmented material at the anchor zone sufficiently to provide adequate anchorage. Clastic dikes along the rib line may be stabilized with bolts installed at an angle and anchored in the compression zone above the pillars (*17, 33*). In this situation, bolts should be installed immediately after undermining, and crossbars or steel mats should be used to stabilize slickensides and prevent spalling of the clastic-fill material. These are most effective if the mats are flexible enough to conform to the shape of irregular roof. The effect of the unsupported cantilever beam that a clastic dike creates in roof rock can sometimes be corrected by bolting and strapping the roof on each side of the dike, depending on the severity of roof deterioration associated with the dike (*17*).

If there is doubt as to the effectiveness of the installed roof support, continuous measuring of rates of roof convergence in the vicinity of the clastic dike can be used to determine if adequate roof support has been provided. Sag rates greater than 0.5 cm/d have been found to correlate with imminent roof failure, suggesting that additional support is needed in those areas. Cribbing may be constructed, or if the entry must be open for transportation and equipment, roof trusses or steel sets may be adequate to stabilize the area (*17, 36*).

Full-column resin bolts have proven effective in controlling some clay veins because grout acts as a seal, preventing moisture from deteriorating the material along the bolt hole, and provides better holding capacity in weak rock (*17, 36*). If slickensides occur only within the clastic fill and the roof surrounding the dike is not too disturbed, the installation of additional bolts oriented at an angle toward the center of the dike can act to bind together the clastic fill (*13*). Where roof deterioration is severe because clastic fill deteriorates upon exposure to moisture and thus causes roof instability, fiber-reinforced concrete or roof sealants can protect the clastic fill from the effects of atmosphere (*17, 36*).

Where clastic dikes are so large that bolts could not support the extensive disturbed zone, or in mines where cutter roof failure occurred in association with clastic dikes, trusses and cribbing effectively supported the roof and prevented cutter roof development. However, they were successful only when installed shortly after mining. In cases of severe cutter roof failure in which large falls spanning several entries have occurred, short-term changes to the mine plan may be necessary. Staggering crosscut locations will prevent the propagation of cutter roof failure down the entry (*40*). If a clastic dike is known to exist where a crosscut is to be turned, turn posts should be used immediately until permanent support can be installed. Turning the crosscut just before or just after the clastic

dike can avoid the problem altogether (*17*). If clastic dikes tend to be oriented along a preferred direction in a given area, reorienting direction of mining to 45° to strike of the clastic dikes will minimize exposure of the features in entries and crosscuts.[10]

Predictive Techniques

Clastic dikes are relatively small-scale features and may easily be missed by exploratory drilling on large-scale drilling centers (*30*). These features have a linear to curvilinear strike and, once exposed by mining, can be projected into unmined sections with fairly good accuracy (*17*). In a given coal basin, clastic dikes may occur in conjunction with more distinguishable features that could be detected by drilling. Clastic dikes controlled by differential compaction may not be as predictable as those controlled by tectonic, structural, or depositional processes. Often clastic dikes have been observed to intrude from the base of rolls in the floor (*37*). Isopach or structural maps of the coal seam may reveal the locations of floor rolls and suggest the possibility of clastic dike occurrence. If a syncline is present in the coal seam structure, clastic dikes might occur along the synclinal axis, oriented nearly parallel or nearly perpendicular to the axial trend (*1, 46*). The structural trend of folds in an area can usually be determined easily and can be used as a tool to predict the presence of clastic dikes once a relationship is established. If it is established that dike trends coincide with the jointing pattern in a given area, joint mapping may be used to predict clastic dike occurrence[11] (*41*). Clastic dikes have been found to occur within the marginal zones of paleochannels in some underground coal mines. Maps projecting paleochannel trends may also be used to predict possible locations of clastic dikes. Clastic dikes associated with paleochannels usually show preferential orientations perpendicular and/or parallel to the paleochannel trend (*3*). If it has been established that clastic dike trends parallel the paleoshoreline or paleotopographic features, isopach maps of key strata exposed in the roof or intersected by drill holes may be helpful in determining such trends. An isopach map of beach sands may be helpful in determining the location of the paleoshore. In an eastern coal mine, thicker areas of a claystone-coal rash layer coinciding with areas of thicker roof shale have been interpreted to represent areas of topographic lows that were more favorable sites for the accumulation of peat and mud (*47*).

[10]Work cited in footnote 3.

[11]Work cited in footnote 4.

MOLD-AND-CAST STRUCTURES OF FOSSIL PLANTS

Definition and Description

Preserved paleotree trunks, stumps, roots, or branches occur in the roof strata of underground coal mines in every U.S. coal basin and are known by a variety of names, such as kettlebottoms, pots, cauldrons, cauldron bottoms, coal pipes, tortoises, and camel backs (*17, 48*). These terms may also be used locally to refer to features that bear a physical resemblance to these fossil plants, but are otherwise unrelated. In this discussion, the term "kettlebottom" refers strictly to a preserved paleotree; it is defined in more detail in the glossary.

Kettlebottoms are mold-and-cast structures in which the form of the tree acted as a mold and was filled with clastic sediments that became the cast. The outer surface of the structure is sometimes covered by a thin layer of coalified bark. The paleotrees were often buried and filled while still in their growth position, thus forming columnar plugs of sediment oriented perpendicular to bedding. When exposed in the mine roof, they appear as discrete circular bodies embedded in the roof rock. Fallen trees or logs can also trap sediment and form a different pattern in the mine roof.

Kettlebottoms show wide variations in diameter, depth of penetration into the roof, and composition of the sediment fill comprising the cast. The diameter normally ranges from 15 cm to 2 m, averaging about 1 m. Extension into the mine roof may range from 0.5 to 2.5 m. The average length varies from area to area, but appears to be consistent in local areas of a coal seam. Kettlebottoms occur in both shale and sandstone roof rock (*17*). The sediment fill that forms the cast was carried in and deposited by currents flowing through the site. The grain size can range from silt to coarse sand, depending on the competence of the depositional currents (*48*).

Sedimentary Environment

In Eastern U.S. coal basins, kettlebottoms formed during the late Paleozoic have been identified to be fossils of large, scaly-barked trees (Phylum Lycopsida), trees with jointed trunks and vertical ribbing (Phylum Sphenopsida), primitive fernlike and palmlike seed-bearing plants (Phylum Gymnospermae), and ferns (Phylum Filicineae). Plant species from these four phyla comprised a major portion of the vegetation in the coal-forming swamps at that time. The coalfields of the West were formed later in

the Mesozoic Era. The Cretaceous swamps of the West were dominated by Phylum Gymnospermae, including the conifers, and Phylum Angiospermae, featuring internal, covered seeds and true flowers (*49*). The root systems were extensive to provide support for the tall plants, which attained heights of 20 to 30 m (*48*).

Paleotrees had soft pulpy interiors surrounded by a tougher outer shell covered by a primitive form of bark. Upon death, the soft interior was quickly decayed by microscopic organisms, leaving only the resistant, hollow outer shell. Often the shell was substantial enough to allow the tree to remain upright in growth position as it gradually became buried and filled with sediments (*48*).

The plant communities, being located on the delta plain, were vulnerable to rapid influx of sediments. Sedimentation events ranged from short, periodic events that occurred at flood stage of the river to longer events such as the shift of a channel route that brought in a constant flow of sediment-bearing currents. The shorter events stifled small plant forms and temporarily retarded growth of larger plant forms until sedimentation ceased; then the community reestablished itself. During the longer events, sedimentation completely overcame the swamp environment, burying it under a substantial load of clastic deposits. The trees that remained in growth position during burial extended into the overlying sediments, which subsequently surrounded and filled them. If the upper part of a trunk broke off before it could be buried in growth position, the broken trunk fell onto the existing substratum and was incorporated into it as deposition continued (*48*).

The lithologic composition of the sediment fill of the cast may be similar to that of the surrounding roof stratum or may correspond to the lithology of a unit lying some distance above the immediate roof stratum. The lithology of the sediment column that forms the cast within the hollow mold of the tree corresponds to the sediment carried by the current that flowed over the open top of the trunk. The distance between the immediate roof stratum and the stratum that corresponds to the cast is determined by the height of the trunk as it was buried in growth position (*48*). The preserved vertical tree trunk in figure 8 was filled with sand and clay, which later became a sandy shale; apparently the adjacent log broke and fell during the deposition of this material. As the coal seam beneath the kettlebottoms in figure 8 is mined, the shale surrounding the root sructure of the vertical tree trunk will probably fall away immediately. In the immediate mine roof, only the roof structure of the vertical tree trunk would then be visible and would appear as a plug of sandy shale surrounded by the shale. The presence of the kettlebottom formed by the horizontal log would be undetectable in the immediate roof, causing a potential hazard.

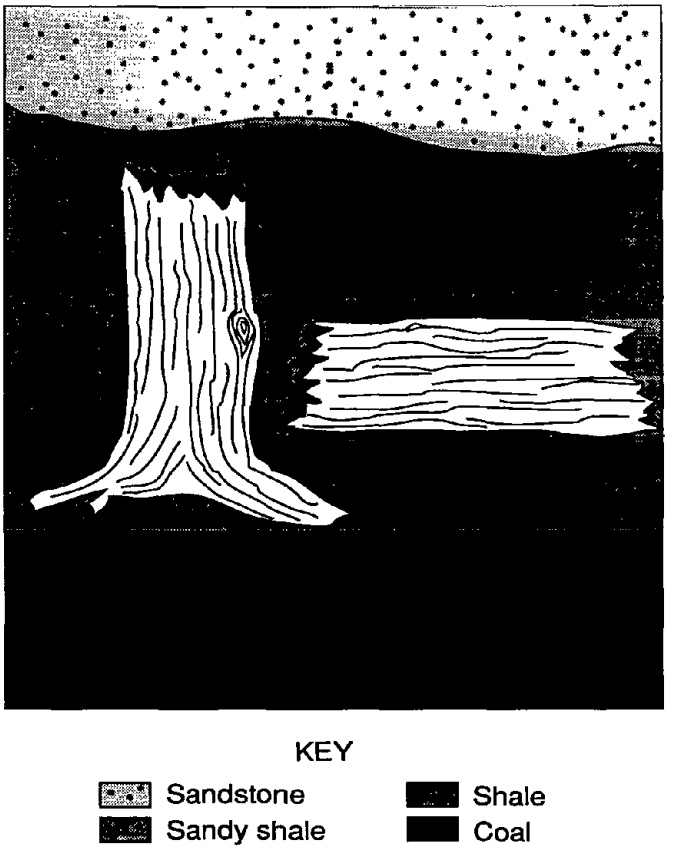

Figure 8.—Kettlebottoms preserved within coal seam overburden, partly in growth position and partly in position where part of the tree fell when exposed to the currents that deposited sand and clay, which later became sandy shale.

The height and diameter of trees of a given species are determined by their age. These parameters fall within a certain range within one plant community, because the majority of individuals within a community are at similar stages of development. For this reason, the height and diameter of kettlebottoms in one area of a coal seam will be similar if all are in the growth position (*23*).

Kettlebottoms tend to occur with greater frequency within coal basins deposited on unstable, rapidly subsiding platforms. These basins tend to have a correspondingly faster rate of sediment influx, which provides the optimal depositional environment for widespread preservation of kettlebottoms (*36*).

Effects on Mining

When kettlebottoms occur in a coal mine roof, they present a safety hazard. Often the surfaces between the kettlebottom and the surrounding roof are highly slickensided from differential compaction. Because it is isolated

from the roof stratum by slickensides or weakly bonded to the stratum owing to a coalified outer layer of bark, a kettlebottom can drop out of the roof readily. Kettlebottoms may be difficult to distinguish from normal mine roof because often the only detectable features are the surrounding slickensides, which may or may not be distinguishable from other slickensides in the roof by a distinctive circular pattern (*4, 17*). Depending on the composition of sediment fill, a kettlebottom can drop out in one coherent unit, or can fall out in slabs separated at weak bedding planes that occur within the cast. A kettlebottom may not detach from the roof at all if it is composed of a well-cemented sediment with little or no marginal coal layer. Even if the kettlebottom does not fall soon after exposure by mining, the potential for failure still exists (*48*).

Kettlebottoms are a safety hazard even when they occur some distance above the coal seam in the overburden strata and are not visible in the immediate roof. Because of their weak bonding to the host stratum, gravity pulls them out of place, allowing them to migrate downward. Similarly, kettlebottoms may be hidden by the few centimeters of head coal left along the roof to protect a rashy shale roof from humidity. The coal cannot provide the support necessary to hold a kettlebottom in place (*9, 21*).

Because of the difference in the geologic time of formation, Eastern U.S. kettlebottoms are slightly different from those in the West. In eastern coal basins, kettlebottoms are usually composed of a columnar mass of the paleotree stump. They are distinguishable in the mine roof by a distinctive circular pattern of the surrounding coal layer and/or slickensides (*17*). In the West, kettlebottoms usually consist of the root structures, which were more developed in the Cretaceous than in the Paleozoic. Western kettlebottoms tend to fail along the slickensided boundaries radiating around the base of the paleotree, forming a concave-upward cone-shaped zone of weakness (*4*). The formation of western coal swamps was also contemporaneous with dinosaurs. Some species of dinosaurs fed from the foliage of the paleotrees (*50*), and their footprints are often associated with kettlebottoms. The weight of the dinosaurs on the spongy peat caused the peat to compact under their feet, forming depressions that were filled by later sediments. Fossil casts of the footprints do not usually contribute to roof instability, but occasionally the underside will be slickensided, causing the underlying rock to fall (*4*).

Recommendations for Roof Support

If a kettlebottom is visible in the immediate roof and does not fall out during or soon after mining, it should be secured in place with permanent support devices. Relying on a single roof bolt in the center to hold the kettlebottom in place is effective only if the bolt is long enough to penetrate the full length of the feature to anchor it in the overlying rock. Vibrations in the roof caused by drilling roof bolt holes may be enough to dislodge the kettlebottom. Angle bolting is a more reliable method, but is probably adequate only for small kettlebottoms. The most reliable method of supporting a kettlebottom is installation of two roof bolts, one on each side, holding a strap in place across the bottom of the feature[12] (*17*). Unfortunately, visible kettlebottoms do not cause roof problems when properly supported; it is those hidden in the overlying strata that fail unexpectedly, even after the area has been adequately supported. In an area where kettlebottoms are known to occur, wire mesh, straps, and/or pans can be used to hold unexpected roof falls resulting from kettlebottoms hidden in higher roof strata.

Predictive Techniques

The presence of kettlebottoms is nearly impossible to detect in advance of mining because of their random distribution within roof strata. Even after they have been undermined, they are often not observable until failure occurs. Sometimes a kettlebottom will slip out of position gradually, causing the roof shale beneath it to bow downward. If the roof has a pattern of rounded knobs or a single rounded dome protruding downward, the presence of an overlying kettlebottom is possible. Even if they occur only a few centimeters above the immediate roof, they are not discernible with the usual roof-sounding methods. Kettlebottoms tend to be associated with particular coal seams and can occur in clusters or singly in an erratic configuration. The occurrence of one kettlebottom may or may not indicate the presence of others nearby; if a kettlebottom is identified, it is safer to suspect that others may be present (*4, 38*).

Because the existence of kettlebottoms is not predictable, the alternative is to employ precautionary measures. When working in an area where there is a chance that kettlebottoms may exist, mine personnel should be aware of the possibility of their presence, and the potential safety hazard, and should know how to recognize them.

CONCRETIONS

Definition and Description

Concretions, also known as nodules, are isolated rock bodies of a composition chemically distinct from the surrounding lithologic unit (*51*). Their shapes range from spherical to ellipsoidal to highly irregular; sizes can range

[12]Stateham, R. M. (consultant). Private communication, 1993; available upon request from V. Shea-Albin, BuMines, Denver, CO.

from less than a centimeter to meters in diameter. The longest axis of a concretion is usually oriented parallel to a bedding plane. They usually occur in groups or clusters. Concretions occur most frequently in shales and limestones, but are occasionally found in sandstones. The chemical composition of most concretions consists of iron and/or carbonate constituents including siderite ($FeCO_3$), limonite ($FeO \cdot OH \cdot nH_2O$), hematite (Fe_2O_3), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and pyrite (FeS_2) (*52*).

Sedimentary Environment

The origin of concretions is not fully understood. They may have formed from some minor chemical constituent in the rock that migrated to some nucleus (*51*). Another alternative is that they developed authigenically through precipitation from a migrating mineralized fluid, similar to the formation of cement within a sedimentary unit (*52-53*). In some cases, concretions appear to have formed by chemical aggregation around a plant or animal fossil (*44*).

Effects on Mining

Concretions occurring within units composed of clay minerals, such as shales and mudstones, tend to disturb the preferred orientation of the platy clay particles, interrupting the inherent strength between clay minerals. Often concretions are characterized by slickensided surfaces. They tend to be denser than the surrounding stratum. Under differential compaction, as the surrounding stratum compacts more than the concretions, slickensides form around them. Therefore, like kettlebottoms, nodules are only weakly bonded in place within the stratum. As a result, they tend to fall out of the roof readily.

Frequently, concretions occur several centimeters to several meters above the immediate roof and are not visible. Concretions observed in the mine roof have been found to be associated with increased water saturation within the host unit, further weakening their bond with the surrounding stratum. Concretions have a higher density than the surrounding lithologic unit. Because of their higher density and their weak bonding to surrounding strata, they tend to migrate downward through the roof. Eventually they break through all confining roof strata and fall free (*51-52, 54*).

Recommendations for Roof Support

A large concretion can be bolted to the roof. However, concretions are frequently small and occur randomly in clusters scattered throughout the roof, preventing bolting from being a practical solution. Figure 9 shows a typical arrangement of concretions and the difficulty of securing them within the roof. As with kettlebottoms, wire mesh, straps, or pans can be used in an area where concretions are known to occur, to control any unexpected roof spalling resulting from concretions occurring higher within the roof strata.

Predictive Techniques

As with kettlebottoms, the presence of a concretion is nearly impossible to detect in advance of mining because of random distribution within roof strata. Concretions occurring above the immediate roof strata may remain stable for a long time until actions such as roof sagging or deterioration or water penetration into the roof loosen them, causing them to fall unexpectedly. Upon failure they may slip downward gradually, causing the roof shale beneath them to bow downward, or they may cause a sudden roof collapse in the immediate area. A pattern of rounded knobs or a single rounded dome protruding downward from the roof may suggest the presence of overlying concretions as well as kettlebottoms. Like kettlebottoms, concretions occurring only a few centimeters above the immediate roof are not discernible with the usual roof-sounding methods. Concretions can occur in any lithologic unit associated with coal-bearing strata and can occur in clusters or singly in an erratic configuration. The occurrence of one concretion may or may not indicate the presence of others nearby. As with kettlebottoms, once the presence of concretions is detected, it is safer to suspect that others may be present and to employ the precautionary measures suggested for control of kettlebottoms.

LITHOLOGIC FACTORS

In addition to anomalous sedimentary features that affect unstable roof conditions, roof instability can be attributed to the inherent weaknesses of the roof lithology. Lithologic features, such as grain-size distribution, cementing agents, and susceptibility to weathering and humidity, influence rock strength. In general, massive, coarse-grained rocks are more competent and can withstand greater weight and stress than thin-bedded or interbedded, fine-grained rocks. Shales often fracture when subjected to stress. Bedding planes and contacts between rock types are zones of weakness and often serve as planes of initial failure (*15, 26*). Because of the effects of differential compaction, facies changes between rock of different physical properties contribute to instability of roof rock. Facies changes occurring both laterally and vertically within the stratigraphic sequence are found more often in coal-bearing strata deposited in a more stable basin, where depositional conditions are more conducive to progradation and lateral offset than to vertical stacking of similar rock types (*36*).

Figure 9.—Concretions exposed in coal mine roof contributing to roof control problems.

Sandstones

Usually sandstones create very stable roof conditions. The ideal sandstone roof consists of a competent sandstone thicker than 4.5 m occurring within bolting distance of the coal. However, some sandstone lithologies are not conducive to stable roof conditions. One such type is hard sandstone known as quartz arenite, which consists of 90 to 100 pct quartz grains cemented by quartz. Its hardness presents problems in roof bolt installation. Quartz arenite is hard enough to allow buildup of stress to a critical point. At this point, the rock responds by fracturing and crushing. It then falls in large jointed blocks (*15, 21*). Such a strong rock resists caving when it occurs over longwall panels and causes stress distribution problems at the face and in the adjacent entries, resulting in bumps and bursts. When stress builds to the point that the strength of the rock is exceeded, failure is usually massive and violent.

Another problem rock type is a crossbedded sandstone that may also exhibit scour-and-fill features and channel-lag deposits. These features are zones of weakness in the rock. The sandstones are often weakly cemented and friable, making it difficult for roof bolts to remain firmly in place.

Another hazardous type of sandstone is known as stack rock, which occurs in thin, flat beds. This type of sandstone is described as being "flaggy" because flagstones are formed from this type of lithologic unit. Mica flakes or coalified plant debris may be concentrated along bedding planes, weakening the unit further. Similarly, a sandstone interbedded with shale, or containing shale or coal partings, tends to fail along these weak zones.

Flaggy sandstone or stack rock tends to occur adjacent to paleochannels in crevasse splay deposits. Crossbedded sandstone tends to occur as channel-fill deposits. Quartz arenites are usually shallow epicontinental sea deposits,

where the sediments were reworked by wave and current action. This action over a long period of time broke down chemically and physically all but the most stable minerals, leaving only well-rounded quartz grains (*52*). Sandstone conglomerates that contain abundant chemically unstable lithic fragments weather readily when exposed to air and water and can become physically weak (*26*).

Roof falls caused by weak bedding planes tend to develop early as roof sag. Even if the roof is supported by roof bolts, the bolts may not be anchored in thick, competent strata. Very thinly bedded sandstone is prone to fail very soon after exposure, especially in intersections where the greatest span of roof is exposed. As sagging progresses, fracturing penetrates the roof, resulting in general disintegration and collapse. Fully grouted resin bolts may help bind the weak bedding planes together in the vicinity of the bolts, but very weak strata will fail between bolts. Trusses, posts, or crossbars may be needed. If all else fails, narrower entries leave shorter spans of weak roof rock to support (*35*).

Sandstones are often aquifers and thus may contain substantial amounts of water. When an aquifier is intersected by roof bolts, fractures, joints, or faults, water can drain from the roof into the mine opening.

The type of cement holding the sediments together is an important factor contributing to the degree of stability. Quartz cement occurs most often in quartz sandstones that are 90 to 100 pct pure. Pure quartz sandstones are characteristic deposits of high-energy depositional environments, including ancient beaches, marine bars, and some fluvial sandbars (*52*).

Calcite cement is found associated with sediments of all depositional environments. Because calcite is highly soluble, especially under acidic conditions, and because it is a weak cementing agent, its distribution within the sandstone can be highly irregular. A sandstone with carbonate cement can vary over a short distance from highly competent to very friable (*52*).

Clay can act as a cementing agent in sandstones. The clay may have been deposited along with a poorly sorted sand in a low-energy environment, or it may have been formed by breakdown of sand-sized feldspars that weather readily when exposed to air and water (*52*). Clay cementation of sand can cause the sandstone to be very friable. When exposed to humid air, the clay loses its competency, and the sandstone tends to disintegrate. Friability in a sandstone often leads to loss of support tension, especially in mechanical roof bolts (*24*).

Shales and Claystones

Fine-grained rocks, such as shales and claystones, tend to be the immediate roof stratum for coal seams. Shales and claystones are typically composed of fine quartz grains and clay minerals, which readily absorb quantities of water. Shales are characterized by thin beds that separate easily, a property known as fissility, whereas claystones are massive without distinguishable bedding planes. The strength of the clay unit depends on the degree of preferred orientation of the platy clay minerals, a property known as fabric. The greater the tendency of the clay particles to be aligned in a preferred orientation, the stronger the unit is physically because of the inherent strength of the bond between clay minerals. The introduction of water disrupts the preferred orientation of the clay particles. Increasing the random orientation of the clay minerals breaks the cohesiveness between particles and reduces the overall strength of the unit. Water also causes cracks to form along the exposed surface of the shale or clay unit. Water then moves along these cracks to further penetrate and degrade the unit. The presence of bedding planes in a shale provides additional pathways to allow water penetration within the unit (*53*).

Air slacking or slaking is a term used by miners to describe the deterioration of mine roof, usually shale, upon exposure to the mine atmosphere. Humidity is the major cause of this degradation, including seasonal changes in humidity of the mine atmosphere. It was originally thought that only rocks with high montmorillonite clay content tended to swell (*31, 51*). Studies have shown that any rock type is susceptible, regardless of physical or mechanical properties, with claystones and shales showing the greatest amount of degradation (*55*). Any rock type adsorbs moisture under humid conditions and releases it at low humidities. Research has provided evidence that the associated expansion and contraction in response to changes in humidity generate sufficient strain in the roof rock to cause extensive fractures. Swelling can lead to relaxation along existing discontinuities such as slickensides, fractures, or bedding planes (*55*). Once slaking begins to occur, it causes the outer layer of rock to swell and separate, creating passageways for water to penetrate farther into the rock, continuing the process inward (*53*). Because shales are fissile, they are even more prone to slaking upon exposure to moisture. The degree to which mine roof strata will be affected by slaking depends on the local climate, variations in roof competence caused by rock type and planes of weakness, and ground control procedures (*55*). The effect is usually seasonal, with summer air being more humid and precipitating more moisture once it enters the mine environment. Winter air is generally drier. When it enters the warmer mine environment, its capacity for holding water vapor increases, so it tends to take moisture from the strata. The effects of seasonal variation are less in the Western United States than in the more humid East because the air in the West tends to be drier all year round and there is less overall variation in humidity (*55-56*). Western mines, however,

are still subject to moisture-related deterioration of mine roof, especially during the more humid summer months (*4*).

Air slaking creates ground control problems for mines. Disintegration of the immediate roof interferes with ventilation and is detrimental to safety and production. Even gradual deterioration of roof rock disrupts the continuity of the roof strata, reducing the effectiveness of roof bolts. The progressive loosening of blocks of roof rock leaves bolts dangling or connected to the roof only by a column of loose rock. At this stage, the bolts are no longer contributing to roof support, and the roof in this area is virtually unsupported. Transportation of supplies and personnel is hampered by fallen material that must constantly be removed (*55*).

The degree to which air slaking will affect the mine roof is difficult to predict. Tests on drill core can give a premining indication of how susceptible the immediate roof will be once it is exposed by mining and can provide some basis for comparing the behavior upon exposure of the different roof rock types that will be encountered within the mine (*55*).

A number of possible preventive measures can be taken to reduce the effects of air slaking. One is installing sufficient initial support in the roof, preferably using resin bolts that act to bind together any planes of weakness or bedding planes within the roof unit. Resin bolts also act to seal the bolthole from water penetration that might quickly deteriorate the rock immediately surrounding the bolt. Coating the roof as soon after exposure as possible with protective sealants, such as shotcrete or gunite, provides skin support to a roof that is prone to deterioration. Tar and polymeric sealants are effective but are more expensive. Because it is the variation in humidity that causes the dilation of the rock that eventually leads to deterioration, sealants should be applied while the roof is still wet from the water applied by the continuous miner during mining. Sealants must be maintained intact to be effective. Because this is an expensive approach, use of sealants is usually limited to critical areas such as haulage ways and the base of shafts. Top coal can be left to protect a susceptible roof unit, but in some cases top coal is difficult to support adequately to keep it in place for long periods of time because of a weak contact between the coal and roof stratum (*56*). Allowing intake air to pass through a tempering or conditioning chamber stabilizes both the humidity and the temperature of the outside air before it enters the rest of the mine workings. Air residence time can vary between 15 min to over an hour, depending on how great the contrast is between the temperature of the outside air and the ambient temperature within the mine. With this method, roof deterioration is limited to a controlled area (*55*). This method is favorable because of its simplicity and relative low cost, and most mine layouts can be adapted to establish tempering chambers somewhere in the mine. Most commonly, older workings that are no longer used for travel and where intake air can course through at fairly low velocities are used for the tempering chambers (*56*).

Some types of shale or claystone are inherently weaker than normal. When these weak units form the immediate roof in the coal mine, they often separate from the roof during the mining of the coal, increasing the ash content, or they separate from the roof later between roof bolts, creating small scattered roof falls or hazardous hanging slabs. Fossiliferous shales are a common lithology in coal-bearing strata. The fossiliferous nature causes this shale to be even more prone than shales generally to separation along bedding planes, because of the lack of cohesion along the carbon plane of the fossil. Black carbonaceous claystone is massive and lacks the fissility that characterizes shales. These rocks are very brittle and fracture into blocks that fall out of the roof. Drawslate or rashy shale characteristically contains coal streaks, crumbles easily, and falls whenever it is exposed by mining. Because it is highly incompetent, when this rock type occurs directly above the coal seam, it is often mined along with the coal to expose a more stable rock type in the roof (*1, 4, 15, 24, 32*).

Fireclays present stability problems in the roof and floor of a coal mine. They are fine grained, sometimes plastic, and often intersected by slickensides (*21*). When they occur in the floor, fireclays become unstable when exposed to moisture and cause poor floor conditions.

Weak floor clays can contribute to ground control problems unless their physical properties and behavior beneath coal pillars have been taken into account for pillar design. Once the coal is mined, the support of the overburden is shifted to the coal pillars, increasing the load on the floor in certain critical areas beneath the pillars. If the floor clay is particularly weak, it can flow away from zones of high stress and lead to floor heave. The outward motion of the clay beneath the pillar can lead to severe rib spalling in some cases (*57*).

Coal

The nature of the coal seam itself can contribute to ground control problems and difficult mining conditions. Some coals have a high gas content. The gas from a coal seam is composed mainly of methane with some carbon dioxide, oxygen, and nitrogen (*1*). Upon mining, the gas is released into the mine air, creating potentially explosive and toxic conditions. Direction of mining relative to cleat orientation can affect the rate at which gas is released from the coal, as discussed under "Cleat." Gases can diffuse out at a constant rate from the coal along cleat planes, or can occur under pressure in pockets and be released with force, causing methane outbursts. When a

coal seam is known to be gassy, methane has been released in advance of mining by drilling holes from the surface and intersecting the coalbed.

A thin bed of coal included in the overburden above the main seam is known as a rider seam. This thin coalbed creates a layer of weakness in the roof strata (*58*). As the main seam is mined, the roof often separates along the rider seam, sometimes even before the roof bolts can be installed. In addition to the rider coal itself being a zone of weakness, rider coals are often underlain by clays that served as the substratum for the original vegetation and contain fossil roots and disrupted bedding from root action. Such rooted clays are also zones of weakness that can allow failure to occur. In some cases rider seams are associated with increased concentrations of methane that has been trapped between the rider and the main coal seam (*32*).

Rider seams are common coal basin deposits. Typically they are thin, discontinuous layers located above the main coal seam (*4*). Rider seams often overlie a crevasse splay sequence, further enhancing a hazardous roof condition (*34*). The thickness of the interval between the rider seam and the main coal seam varies at different locations within the mine. Depending on the thickness of the interval between the coal seam top and the rider seam, roof problems can result from the weak anchorage zone provided for the roof bolts (*32*). When a rider seam occurs in the roof above the extent of the roof bolts, a fall encompasses all the material up to the rider seam (*23*). Longer bolts may be needed to anchor in a more stable horizon above the rider seam. It is important to track the location of the rider seam in the roof in relation to the length of the bolts being used. Drilling test holes will determine the distance between the rider seam and the main coal seam. The rider seam may occur so close to the main coal seam that the intervening strata may separate during mining, increasing the ash content and adding to the burden of the coal-cleaning facilities. In some cases, it is easier to mine the rider seam, if the intervening strata are not too thick, than to attempt to support the weak contact in the immediate roof. If the interval between the rider and the main coal seam consists of an incompetent unit, such as drawslate, it may be removed during mining to leave the rider coal as the immediate roof protecting the overlying shale from deterioration by moisture (*3*). If the interval between the rider and the mined seam is too great to be spanned practically by conventional bolts, cable bolts or truss bolts may control the weak roof conditions.

The contact between the coal seam and the immediate roof rock may be a zone of weakness that affects the ground control procedure in the mine. The contact between coal and the immediate roof rock is generally smooth and in some areas has experienced lateral displacements, called bedding plane or interface slip, prior to mining. Research has shown that the very low frictional properties along the coal-roof rock interface can significantly reduce pillar strength, emphasizing that the effects of this interface slip should be considered in pillar design within the mine. As interface slip occurs along the coal-roof rock contact after mining, the vertical loads on the pillar are transferred toward the pillar core, which may induce further interface slip. If the frictional resistance of the entire interface is exceeded, the end result may be either a gradual or a violent lateral movement of the pillar into the mine opening (*59*). Close observation of the bedding plane between the coal seam and the roof rock in drill core and in the underground workings should provide an indication of the type of contact that exists between the two units. If there is ready separation of the two units along this contact, or if fossils occur along the bedding plane to further weaken the contact, a low coefficient of friction should be assumed. Slickensides observed along the contact indicate that horizontal movement has occurred along that very weak interface.

Discontinuous Bedding and Facies Changes

The continuity of a stratum is an important factor affecting stability. Even a competent rock type will exhibit unstable behavior if it is not laterally continuous. An abrupt termination of a stratum can be caused either by the action of erosion or by changing sedimentation patterns known as facies changes. Discontinuities can also result from the shifting of unconsolidated sediments after deposition. The pressure of overburden can cause a more plastic or water-saturated sediment to flow laterally and intrude adjacent strata (*18*).

The abrupt termination of a stratum is known as a pinchout. Pinchouts frequently occur adjacent to paleochannels in crevasse splays, as previously discussed. Lenticular bedding represents a shift from a high-energy to a lower energy depositional environment, as with a migrating stream channel or a prograding delta. An abrupt change of lithology causes instability by weakening the beam strength of the affected stratum (*12*). The situation is further complicated by the effects of differential compaction when discontinuous strata create an area where adjacent sediments have highly contrasting physical properties.

Facies changes, although prevalent in coal-bearing strata, are difficult to anticipate in advance of mining (*47*). Western coal basins were subject to erratic and rapid transgressive and regressive cycles in which the sea level episodically encroached upon land and then withdrew. As

a result, western coal-bearing strata exhibit greater lateral and vertical variability in lithology (*4*). The effects of differential compaction will be more severe in this type of environment, which is characterized by discontinuous lithologic units caused by facies changes (*36*). A particularly hazardous type of roof common in western coal mines is an interfingered shale and sandstone unit. In general, the most rapid facies changes occurred along the delta plain, where there was constant interaction between fluvial processes and oceanic tidal processes. The rapid transgressive and regressive series that occurred in the West during the Jurassic and Cretaceous periods intensified these facies changes, creating the end result of multiple variations in sediment over a relatively small spatial distance (*4*). It is not easy to anticipate abrupt cyclic changes in roof lithology in advance of mining. Studies have shown that there is comparable lithologic variation in surface exposures of coal-bearing strata and underground mine workings. Detailed mapping of surface and underground exposures can help indicate the type and rapidity of lithologic changes that may be encountered underground. More closely spaced test drill holes in these areas will be of some help, but economic factors place restrictions on the number of drill holes. As mining progresses, test drilling underground using the roof bolter can provide information on the immediate roof when increased frequency of lithologic variation in the mine roof is causing ground control problems (*47*). Identification of the location and orientation of the paleoshoreline within a given coal basin through mapping and correlation of drill logs can at least isolate the general zone over which facies change tend to occur.

STRUCTURAL FEATURES

FOLDS

Definition and Description

A fold is a bend in strata caused either by soft sediment deformation or by stresses of tectonic origin acting on lithified strata (*53*). This section discusses folds of tectonic origin. A fold of either origin is evidence that ductile deformation has occurred in originally flat-lying beds that were subjected to various conditions of stress, hydrostatic pressure, pore pressure, and temperature (*60*). Folds vary in symmetry, degree of curvature, and size. Variation in symmetry and degree of curvature can range from a monocline through an anticline and syncline to a recumbent fold. A monocline (fig. 10*A*) is a one-limbed flexure in strata, that are otherwise flat lying except for the flexure itself, or a steplike bend in otherwise horizontal to gently dipping beds (*53*). An anticline (fig. 10*B*) is an arch-shaped fold in which the oldest strata are located in the core. A syncline (fig. 10*C*) is a U-shaped structure in which the youngest strata are located in the core (*60*). When a fold is so tight that the limbs are parallel and overturned, as shown in figure 10*D*, the fold is said to be recumbent (*53*).

Folds vary in symmetry when limbs have different dips, such as the asymmetrical anticline and syncline shown in figures 10*E* and 10*F*. The orientation of a fold is described by the orientation of its component parts (fig. 10*G*). The hingeline or fold axis of the fold is the part with the smallest radius of curvature. The hingeline is flanked by areas of large radius of curvature called limbs. The axial plane intersects the hingeline of all the strata in a fold (*60*). A recumbent fold has a horizontal axial plane (*53*). Orientation of the hingeline and axial plane describes the orientation of the fold. The orientation of the hingeline or fold axis is described as plunge and direction of plunge, while that of the axial plane is described by dip and direction of dip. An anticline, which has a fold axis that plunges in two directions, is a dome (fig. 10*H*). A syncline, which has a fold axis that plunges toward the center from two directions, is a basin (fig. 10*I*).

Method of Formation

Folds develop in lithified, flat-lying strata in response to the local stresses induced by regional tectonic forces. The hingeline of the fold forms perpendicular to the local direction of maximum compression. The shape of the fold is controlled by the behavior of the several layers of rock strata involved. The different layers have different mechanical properties, dependent upon lithology, cement type, bedding thickness, and other variables. After development of initial flexure in the strata is complete, the shape of the fold is controlled by one or two of the most competent strata. The weaker layers are constrained by the stronger layers and are deformed in a manner dictated by the more competent layers. The folding layers do not maintain their original thickness as they are deformed (*60*). They thicken in some areas and thin in others. For example, coals tend to be thicker in synclinal troughs (*32*).

Associated Features

As strata are folded in response to tectonic forces, their deformation is controlled by their individual physical properties. Some lithologic units are able to deform in a more ductile manner, while more brittle units are pulled apart. Boudinage is the breaking up of a stratum into small

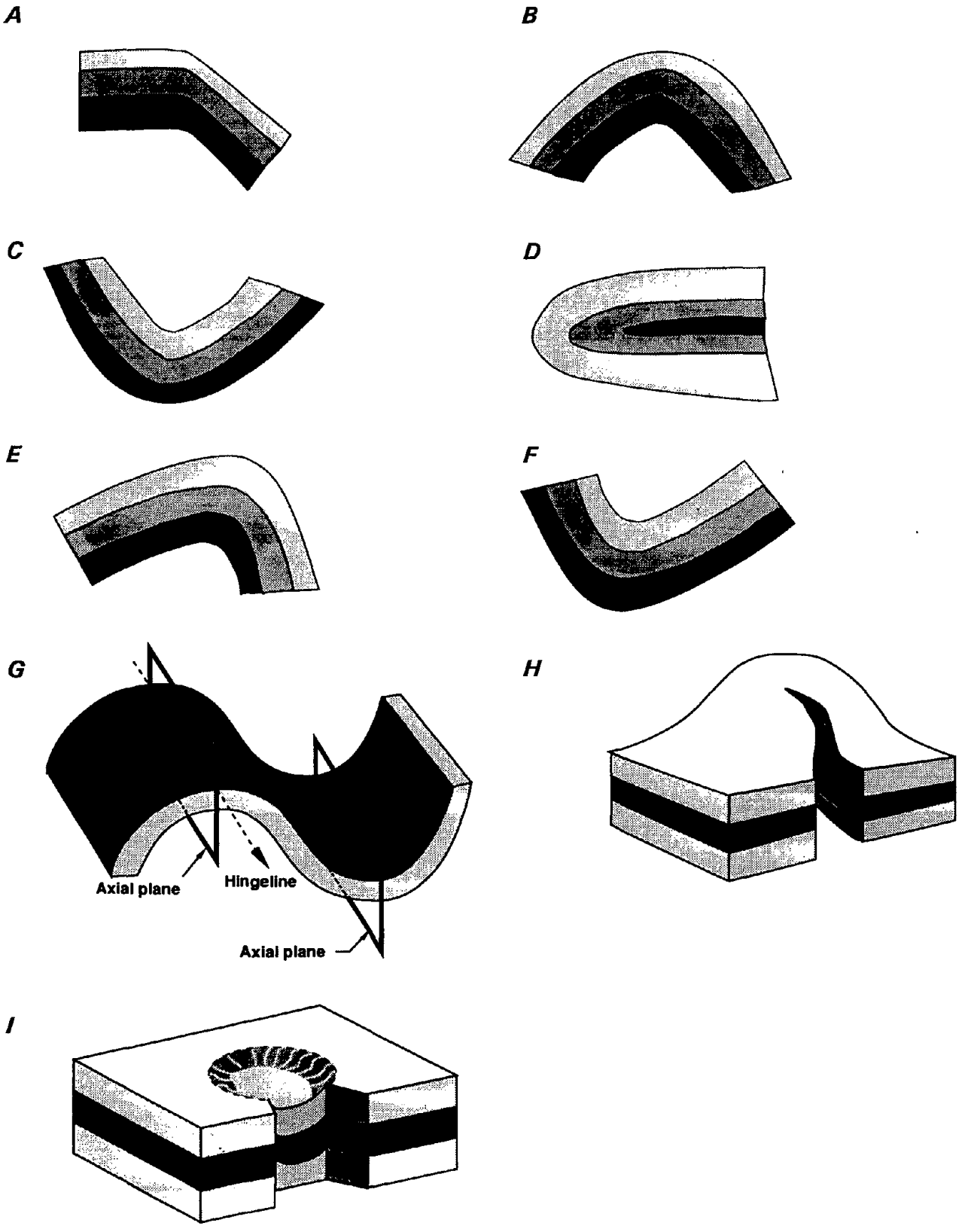

Figure 10.—Configurations of folded strata. *A*, Monoclinal fold; *B*, anticlinal fold; *C*, synclinal fold; *D*, recumbent fold; *E*, asymmetric anticline; *F*, asymmetric syncline; *G*, hingeline and axial plane of folds; *H*, dome; *I*, basin (cross section).

blocks by tensional deformation. It occurs in a unit that is more competent than the units surrounding it (*61*). The competent unit resists tensional deformation and finally breaks, while the less competent units deform readily and flow to fill in the gaps formed by the broken unit.

During folding, the individual rock strata may shift relative to each other, because those near the center of the fold have a smaller radius of deformation than those near the outside of the fold. The relative motion between adjacent strata is called bedding plane slip. Evidence of bedding plane slip is seen as slickensides, which record the direction of local relative movement. A zone of weakness can develop along a bedding plane slip. When such a zone occurs in roof rock above a coal seam, the roof strata will separate along this plane.

Near the hingeline of folds, where the radius of curvature is greater, the frequency of joint occurrence and coal cleat spacing increases.

Effects on Mining

Folds cause strata to have varying degrees of dip, ranging from shallow to steep. Degree of dip can change from place to place within the fold. Steeply dipping coal seams present special problems for mine design. Steep grades complicate transportation and haulage. Mining techniques have been developed to facilitate the mining of steeply dipping coal seams; however, they are not addressed in this paper.

Although the dip of strata may be shallow, there is still an adequate gradient to propel ground water down dip. The flow of ground water through mine overburden strata can cause problems when the aquifer is intersected by fractures or roof bolts, or when the coal seam itself is an aquifer. The hingeline of a syncline, being the low spot, collects pools of water. In general, the presence of water decreases roof and rib stability and lubricates any existing planes of weakness in the roof. The mine water flows down dip along the limbs, collects there, and must be pumped out. When the direction of mining is such that the face is advancing down dip, extensive pumping and piping systems may be required to remove water from the face area (*58*). Mining in the up-dip direction allows water to flow away from the face. Although not specifically a ground control problem, water softens the floor and causes slippery conditions for machinery and personnel, increasing the chances for accidents to occur, especially on the inclined slope of a dipping fold limb. When newer mines are adjacent to old abandoned workings in folded strata, the older mines are probably flooded. The newer mining operation may have to contend with the threat of possible inundation when mining near the abandoned workings (*32*).

Folded strata in the mine environment also affect gas flow, in turn affecting efforts to degas the coalbed in advance of mining. Even a dip of 1° can decrease gas flow, because water must be displaced uphill before gas can flow freely. The hingeline area of an anticline forms a local high pocket in the strata. Gas can migrate upward to this point and become trapped there. Gas or water pushing the trapped gas from below can cause a local increase in gas pressure in the hingeline pocket (*1, 32*).

There is often an increase in fracturing and joint spacing near the hingeline of both anticlines and synclines that can cause roof instability (*32*). In coalfields located within the high western plateaus, folding usually is gentle to moderate. However, some western coal basins have experienced greater deformation, and several western mines are located in steeply dipping seams. When the incline is gentle, the effect on roof control is minimal. Nearer the hingelines of folds, where the degree of curvature is greater, jointing and fractures contribute to roof instability (*4*).

Recommendations

The effects that folds have on mining often do not involve ground control as much as production rates owing to the steep grades and increase in water and gas flow. Steeply inclined entries along dipping fold limbs can be avoided by reorienting entries so that they are not parallel to the direction of maximum dip. Water inflow due to the gradient of dipping strata can be pumped out of the mine workings. Dewatering wells can be installed in advance of mining to reduce the amount of water temporarily in the vicinity of mining. Gas wells can be drilled to degas the hingeline of an anticline so that pressurized gas pockets will not be encountered during mining (*32*).

Predictive Techniques

Large-scale folds are fairly easy to recognize through surface geologic mapping. Surface outcrops provide strike and dip information that will reveal that the strata in an area are folded. Aerial photographs and satellite images are also useful for detecting folds.

FRACTURES, JOINTS, AND CLEAT

Definition and Description

Fractures, joints, and cleat are structural discontinuities in rock strata that result from brittle deformation. They are approximately planar discontinuities with no displacement parallel to the plane of the fracture, joint, or cleat face (*60*). Joints occur as families of fractures displaying similar orientation, spacing, and extent in a given rock

type, whereas fractures occur singly. Cleat is a special case of fracture systems that are analogous to joint systems but occur in coal.

Fractures

Fractures form after lithification when sediments reach the brittle stage and no longer deform in a ductile manner. Fractures form as cracks along which cohesion is lost. The fracture faces can be recemented after fracture formation, either by precipitation of secondary minerals from solutions flowing through the fracture or by recrystallization of original minerals in the host rock. Fractures can remain open with varying amounts of space between fracture planes (*60*).

Joints

Joints can be classified geometrically or genetically. Classification according to geometric associations relates joint orientation to bedding strike or dip or another oriented feature of local rocks. This type of classification is only descriptive. Strike joints are parallel to the strike of the local rock units. Dip joints are parallel to direction of dip. Oblique joints are oriented at some angle to strike and dip of bedding (*62*).

Genetic classification of joints is more difficult because some knowledge of origin is needed to group joints of similar origin. Shear or tensional joints are classified according to the nature of the stress field in which the joints were formed. Genetic classification is usually applied according to the orientation of a stress field that once existed as inferred from other structural features independent of the joints (*62*). In the Eastern United States, joints of the type called hillseams or stress-relief joints are believed to have formed as a result of local stress relief rather than from tectonic forces. They have a nearly vertical dip oriented perpendicular to bedding, occur in shallow overburden where there is high topographic relief, and tend to strike parallel to surface contours. Stress-relief joints are highly weathered from downward percolation of ground water (*63*).

Joints related by common origin are grouped into a set. Joints within a set are often, though not always, parallel. Individual joints within a set may be oriented parallel to the axial plane and normal to bedding planes of a fold, rather than parallel to each other. In addition to changing character according to location relative to limbs or the hingeline of a fold, joints within a set can vary with change of host rock type and with proximity to a major fault. In most rock types, joints extend from tens of square centimeters to hundreds of square meters (*60*).

Spacing between joints can vary from several centimeters to tens of meters. Joints within a set are usually not of the same extent. A set is usually composed of many small inconspicuous joints that are more closely spaced and a few larger joints that can be traced for several kilometers. These large joints are known as master joints (*60*).

In rock types with layered configurations, such as the bedding planes in coal-related strata, the most prominent joints are usually oriented at a high angle to the bedding. Even where the beds are folded, the orientation relative to layering is maintained. Joints parallel to the axial plane of a fold and approximately normal to bedding are radial joints (*60*).

There is also variation within a joint set of the size of the joint opening. Some joints are hardly more than a barren hairline crack with joint faces tightly closed. In some joints, the faces show various distances of separations and form open fissures. In other cases, the joint faces are cemented closed with secondary mineralization, mainly quartz and calcite deposited by solutions flowing through the joint system or by recrystallization of minerals within the host rock. If these remineralized joints are reopened, they form mineralized open fissures (*60*).

Joints form in rock strata as a result of local stress changes within and surrounding the strata or of regional stresses that influence the rocks. Decrease of overburden load of strata by erosion is one method by which a local stress field is varied. As upper strata are removed by erosion, underlying strata bear less vertical load from the weight of overburden. Rocks experiencing decompression expand perpendicular to the free surface, forming a characteristic joint pattern. Local nonhydrostatic stress caused by decompression may be an important influencing factor in joint formation, even when regional deformation is also influencing the deforming rocks. Differential volume change is another method of local stress development. In coal-bearing strata, different lithologic units are juxtaposed vertically in layers and horizontally in lenses. When the lithologic package experiences erosional unloading or subsidence within a depositional basin, local deviatoric stresses are established within the rocks. Because different rock types have different compressibilities, they respond to stress changes at different rates, encouraging the formation of joints (*60*).

One method of classifying joint sets according to their origin is based on the size of the shear component that was present at the time of joint formation. If the shear component is zero so that shear stress at the moment of joint formation is in a direction normal to the joint face, then the structure is classified as an extension joint. If the shear component has some finite value, the structure is a shear joint (*60*). Fractures that form in a body of rock subjected to directional compressive force are usually oriented approximately 30° to the major axis of compression. These fractures form at an angle of about 60° to

each other and are classified as conjugate shear fractures or joints. Shear joints can form at any angle other than 90° to the principal direction of stress (*62*). This genetic classification of joints may be complicated by later directional stresses that acted along joint planes but were unrelated to the stresses that initially formed the joint. Later displacements may be recorded by slickensides on the joint face or on minerals coating the face or by oriented fibrous mineral growths (*60*).

Extension joints in rock form perpendicular to one of the principal stress directions, usually to the maximum compressive force. Otherwise there would be a finite shearing stress component at the point of joint formation, and a corresponding finite shear displacement would occur upon joint formation (*60*). A regional confining pressure affecting an area may decrease over time. The relaxation of this force will permit elongation to occur in the rock body parallel to the principal axis of stress. Joints that form as a result are oriented parallel to the major principal axis of stress by reduction in compressive forces. Such joints are called release joints because they were formed by the relaxation of the compressive forces, although compressive stresses were still active in the area (*62*).

Several joint sets of different origin usually occur together at angles to each other. The joint sets present in an area form a joint system. A fundamental joint system is the basic unit composed of two joint sets that are approximately orthogonal. One set is systematic, and the other is nonsystematic. The systematic joint set is composed of strong, parallel joints. It is the set that intersects all other joint sets and shows the greater vertical persistence (*62*). The origin of the systematic joint set is extensional stress, and joints are formed perpendicular to the axis of least compression. The nonsystematic joints may be release fractures that formed later from the action of stress release. The dominant systematic joint sets mapped in the field are usually nearly perpendicular (*64*).

Cleat

Cleat is a specialized system of joints that occurs in most coalbeds oriented approximately normal to the bedding plane. It is usually composed of a fundamental system of two approximately orthogonal sets. The dominant set is the primary or face cleat, and the minor set is the secondary or butt cleat. The face cleat system is more persistent horizontally and vertically. A face cleat plane can often be traced for several meters and crosses bedding planes within the coalbed, maintaining a consistent orientation. A butt cleat plane may extend only a few centimeters, terminating against face cleat planes, and tends to vary in orientation (*1*).

The origin of cleat in the coal seam varies from region to region. Because cleat orientation often coincides with that of joint sets in associated rock units, it is thought to be related to the joint formation mechanisms that were active in that area in geologic history. Cleat results from brittle deformation of the coal, whether it be a response to regional tectonic stress fields or to lithification processes such as desiccation of the coal-forming peat, flexure in the rock units as the coal basin subsides, or tension in the weaker coal unit resulting from weight of overburden (*65*). Using the spacing of joints occurring within different lithologic units as an indicator of the relative timing of joint formation in response to regional stress, it is thought that joints tend to develop in coal first, and then to form in shale, limestone, and sandstone, in that order. Because coalbeds are relatively incompetent, they can be fractured early in their diagenetic history. Coal cleats have the closest spacing. Joints in shale exhibit the next closest spacing, followed by limestone. The joints in sandstone are the most widely spaced and are most prominent. Because coals are brittle and weak, they develop joints early in response to small stress changes. Coals, therefore, may be considered sensitive indicators of early stress changes, such as subsidence of the sedimentary basin (*64*).

The orientation of cleat tends to parallel the orientation of major joint sets in overburden. Face cleats tend to be perpendicular to the axial trend of major folds in the area. Face cleats probably form as a result of tensional stresses. Butt cleats tend to be parallel to the axial trend of folds and probably formed after the compressive forces relaxed (*1, 65*).

Effects on Mining

Unstable roof conditions may result from structural discontinuities such as fractures, joints, and cleat. Fractures oriented parallel to the main entries of the coal mine are often unsupported by coal pillars and contribute to unstable ground conditions. When these fractures are closely spaced, they can create areas where roof falls are localized as a result of stress redistribution in the roof during mining. When fractures of this nature occur in room-and-pillar mines or in main development entries of longwall mines, they can cause ground control problems. When they occur above longwall panels, they can improve the caving characteristics of the roof (*58*).

Fractures provide open pathways within the stratigraphic sequence for water and gases originating in remote strata to travel into the void formed by coal excavation. Fractures can intersect in the mine roof, isolating blocks of rock called horsebacks that are difficult to stabilize with roof bolts. Fractures have been associated with a condition known as checkerboard roof or keystone roof, in

which there is a high frequency of small roof falls and constant spalling of the mine roof (*32*).

Joints present roof problems similar to those caused by fractures. The orientation of the mine workings relative to that of the joint system influences roof stability. Because joints occur in systems of intersecting sets, they can isolate blocks of overburden rock that separate from the roof upon mining. Joint planes with vertical dips oriented perpendicular to bedding are particularly troublesome. When roof rock containing vertical joints is undermined, there may be isolated blocks in the roof not even partly supported by pillars. These blocks are held in place only by the frictional forces along the joint plane or by compressional horizontal stresses (*66*).

Hillseam or stress-relief joints are a different type of joint associated more with ground control problems in eastern coal mines. Other types of joints are associated with ground control problems in western mines owing to the massive sandstone units that were deposited in rapidly subsiding western coal basins (*4, 63*).

The hillseam joints isolate blocks of roof rock that disrupt the continuity of roof strata. The joints may not penetrate down to the coal seam and, therefore, may not be visible in the immediate roof strata, which hide the discontinuities (*63*).

In the western coal basins, few roof falls have been attributed to joints alone, but when other weaknesses occur in the roof, roof fall boundaries are often defined by joints (*4*). Joints occur most prominently in the thick sandstones that occur in the western coal basins. Because the strength of the roof is controlled primarily by these thick sandstones, joints are more disruptive to ground control in the West than in the East, affecting both rib and roof stability. Joints separate the roof into blocks. If joints are not closely spaced, there is not a significant loss of roof stability. If joints are closely spaced or accompanied by noncohesive bedding, slabs or blocks can fall between bolts, even when extra bolts and steel straps are used. Jointing often occurs in paleochannel sandstones, contributing to the already weak conditions caused by paleochannels. If a prominent joint set strikes parallel to mining, pillar slabbing occurs, widening mine openings and creating a larger span of roof to support. Even if jointing occurs at an angle to mine workings, spalling of pillar corners can require additional roof support (*4*).

Well-developed cleat contributes to roof control problems when the coal pillars slab along cleat faces, thereby reducing the effective size of a pillar (*58*). When cleat dips toward the working face, large blocks of coal may separate along the cleat plane and fall into the working area during mining, constituting a safety hazard. In longwall mines, when strike of cleat is perpendicular to direction of mining, abutment pressures that develop in the working face during mining cause separation of large blocks of coal, which fall from the longwall face along a cleat plane. These slabs can be hazardous for personnel who happen to be present near the face; also, they may be too big for the face conveyor to handle and must be cleaned up manually (*66*).

Cleat orientation creates a directional permeability, controlling the flow of gas and water within the coalbed. If the working face is perpendicular to the face cleat, more gas and water can flow into the mine workings than when the face is parallel to the face cleat (*1*).

Recommendations for Roof Support

In locations where fracture and joint trends parallel entries and crosscuts, stabilizing the roof is more difficult than when fractures trend at an angle more oblique to mine workings. In longwall mines, advancing the face at an angle to roof joints and cleat enables any blocks isolated by roof joints to be at least partly supported by the self-advancing longwall shields (*66*). The dip of the fracture or joint plane is an important factor to consider when stabilizing the immediate roof. Fractures and joints that are oriented at a high angle to the plane of the roof are generally more difficult to support than low-angle fractures and joints, which can often be stabilized by tensioned anchor bolts installed at an angle roughly perpendicular to the fracture or joint plane. High-angle fractures, especially those that occur in closely spaced sets within intersections and entries, may require roof trusses that hold the roof in horizontal as well as vertical compression, to increase the friction along the fracture planes and hold the roof together (*10*).

Mining in a direction 45° to the orientation of the face cleat helps to reduce instability from ribs slabbing along face cleat planes, although the two opposite corners of the pillars may continue to slab along cleat faces (*1*). These corners may be reinforced by bolts and mesh, or the roof above the spalled corners may be resupported by posts or bolts installed after spalling has stabilized.

The increased migration of coalbed gas along the direction of the cleat can become an asset rather than a detriment. In the process of degassing coalbeds in advance of mining, it has been demonstrated that horizontal drill holes oriented perpendicular to the face cleat planes yield significantly more gas flow than holes drilled perpendicular to the butt cleat. This directional permeability is also important in the placement of vertical and slant degasification holes drilled from the surface into the coalbed. It is beneficial for the drill holes to be oriented to intersect as many face cleat planes as possible (*65*).

Predictive Techniques

When brittle deformation features, such as fractures, joints, and cleat, form in response to regional stress, their orientation is related to one of the principal axes of the current or ancient stress regime and, therefore, is not random. It is possible to determine whether or not cleat and joints were formed by tectonic forces by observing features such as slickensides, plumose structures, and pulverized coal or rock along the cleat and joint surfaces. Once it has been established that the cleat orientation in a coalfield is related to local tectonic stresses, mapping surface features in an area will provide an indication of the direction of regional stress that affected a given area. However, faults in the coalfield can change the orientation of cleats and joints formed by regional stress. Rotation as great as 90° from the regional trend have been observed near major faults in the Wasatch Plateau region (*66*).

Surface fractures and joints can be mapped and plotted on an equal-area diagram or a rose diagram to reveal the dominant trends in the area. Once the major stress axes have been established, a relational pattern in fracture and joint orientation emerges.

Analysis of satellite imagery provides another method of mapping major fractures and joints in an area. Major fractures and master joints that are persistent for hundreds of meters are visible on aerial photographs or satellite images. Image processing can provide edge enhancements to highlight these discontinuities (*32*).

Cleat orientation in an underlying coal seam can be estimated through an analysis of local surface joints. By determining the orientations of the major joint sets in an area and pairing the sets into all possible combinations of fundamental systems, a dominant system with nearly perpendicular orientation should emerge. This fundamental system is often a good estimate of cleat orientation at depth in some coal basin locations (*67*). In other coal basins, joint sets have little correlation to cleat orientation at depth. In these cases, measurements of surface cleats are better indications of cleat orientation at depth (*62*).

FAULTS

Definition and Description

A tectonic fault, another example of local brittle deformation, is a planar discontinuity between blocks of rock that have been displaced relative to each other by tectonic forces acting regionally. When a number of faults of similar orientation occur together, they form a fault zone. A number of fault zones of similar origin, but not necessarily similar orientation, form a fault system. In contrast to nontectonic faults, tectonic faults occur in well-defined systems that may extend for kilometers, intersecting many stratigraphic layers. A shear zone differs from a fault zone in that no distinct fault planes can be detected because the local deformation is ductile (*18, 60*).

A number of different kinds of faults are formed by different stress fields and characterized by the type of movement along the fault plane. The orientation of the fault plane is described by its strike and dip. The strike is the trend of the line defined by the intersection of the fault plane and a horizontal surface, such as the ground surface or a map surface. The dip is the angle the fault plane makes with a horizontal surface. The strike and dip measurements can vary along the trend of the fault plane. Once strike and dip are defined locally, movement along the fault plane can be resolved into two component directions, dip slip and strike slip. Dip slip is movement parallel to the direction of dip of the fault plane; strike-slip movement is parallel to the strike of the plane. The block of rock above the fault plane is known as the hanging wall; the block below the fault plane is known as the footwall. Degree of dip separates high-angle and low-angle faults. High-angle faults have a dip greater than 45°; low-angle faults have a dip less than 45°. Offset along a fault plane can be analyzed by measuring the offset of a feature (P and P') crossing the fault plane (fig. 11). The vertical component of dip separation is known as the throw, and the horizontal component is known as heave. Net slip is a measurement of the offset between two formerly contiguous points in the hanging wall and footwall (*18, 60*).

The type of fault is determined by its geometric orientation and the direction of movement along the fault plane. Normal, lag, and reverse faults are primarily dip-slip faults, usually showing little or no movement in the strike-slip direction. Normal faults (fig. 12) usually have a high-angle, nearly vertical dip. In normal faults, the hanging wall has moved downward relative to the footwall. When normal faults occur together, the principal stress component perpendicular to the fault planes is tensional. A block of rock formed by tensional forces that has moved downward under the influence of gravity, forming a topographic low between two high-angle faults, is a graben (fig. 12). The relatively uplifted block between high-angle faults is a horst (fig. 12). The faults bordering horsts and grabens are usually normal faults. A reverse fault is also a high-angle dip-slip fault, but the hanging wall has moved upward relative to the footwall (fig. 13). A thrust fault is a low-angle reverse fault in which the reverse movement is inferred rather than supported by direct evidence. Thrust faults may curve at the bottom to merge with a bedding plane. A bedding-plane fault occurs along a contact between units of different lithology, or between beds of the same lithology. This type of fault is difficult to recognize in a mine roof because there is only subtle evidence of apparent off-set, consisting of broken or crushed rock, slickensides, or smeared fossils (*18*). Bedding plane faults

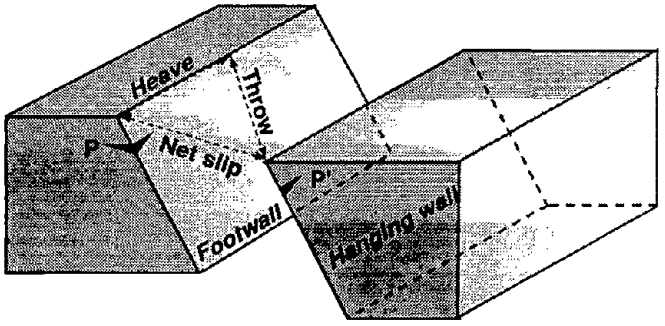

Figure 11.—Fault offset of geologic feature P and P' measured along fault plane.

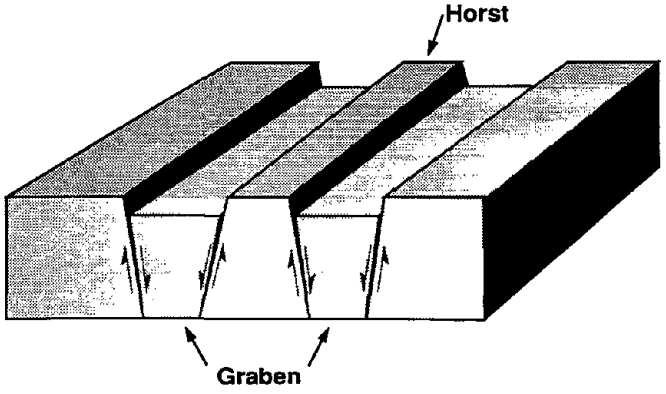

Figure 12.—Normal faults with graben and horst features.

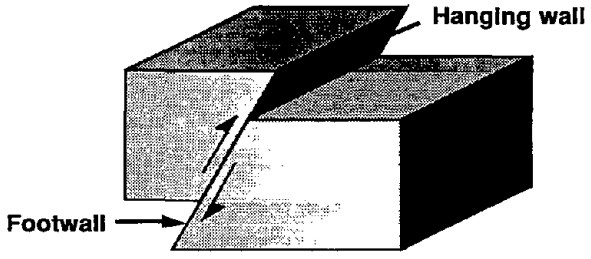

Figure 13.—Reverse fault.

have also been observed to occur in conjunction with strike-slip faults (*68*). A window, or fenster, is an exposure of underlying rock through the overlying thrust fault block. A klippe is a remnant of the overlying thrust block surrounded by rock underlying the fault plane (*60*).

Strike-slip faults usually have very steep to vertical dips. They are also called transcurrent or wrench faults. A strike-slip fault is further classified by the direction of movement along the fault plane. From a viewpoint along the strike of the fault, if the left block has moved toward the viewer, it is a sinistral, or left-lateral, fault (fig. 14*A*).

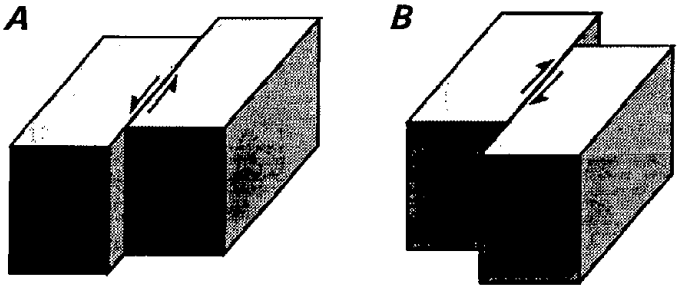

Figure 14.—Strike-slip faults. *A*, Left lateral; *B*, right lateral.

If the block to the right has moved toward the viewer, it is a dextral, or right-lateral, fault (fig. 14*B*). A fault in which the strike-slip and dip-slip components are of nearly equal magnitude is an oblique-slip fault (*60*).

Associated Features

Fault planes are often filled with material fragmented by movement along the fault plane. Angular fragments in a matrix of finely ground rock are called fault breccia. Fragment size of fault breccia can range from microscopic to several centimeters. Pulverized rock of a claylike consistency formed by the grinding of rock during movement along the fault plane is gouge. Soft microbreccias are called pug or gouge. Hard microbreccias may demonstrate platy or streaky "flow" structure. A microbreccia that fills faults in wider zones of intense deformation is called mylonite. Secondary minerals, usually quartz and calcite, sometimes pyrite, may fill open spaces within the fault breccia (*18*).

Slickensides, very common features associated with faults, are formed by movement along the fault plane and are often diagnostic of that movement. The striations along the slickensides are believed to be parallel to the direction of movement during their formation. Slickensides with striations usually contain small steplike features facing in the same direction and oriented more or less normal to the striations. There is controversy as to whether or not these steps are indicative of direction of movement along the fault plane (*60*). More pronounced parallel furrows along the fault plane are mullions. Mullions are larger than slickensides and are not as easily erased by subsequent movement (*18*).

Fault drag features consist of stratigraphic layers bending adjacent to the fault plane. Drag features can be indicative of the direction of fault movement, but this is not always the case. Drag features that display movement in the same direction as fault movement are known as normal drag. Features that indicate movement opposite to that of actual fault movement are known as reverse or

false drag. Both kinds of drag are common, particularly in areas of flat-lying sedimentary rocks. Normal drag is thought to express an early history of limited ductile deformation before brittle failure when the fault formed (*60*). Because normal drag is caused by friction along the fault plane during movement from compressional forces, it is rarely observed near normal faults, which are formed by tensional forces (*18*).

Effects on Mining

A fault zone intersecting mine workings can cause ground control problems and other difficulties, the severity of which depends on the amount of fault displacement, the spacing between faults, strike and dip relative to direction of mining, and the amount of crushing of rocks from fault movement. The amount of displacement and the direction of movement can vary along the strike of the fault. In one area, the offset may be a few meters and require only a small amount of roof or floor rock to be excavated to continue mining, but farther along strike the displacement may be great enough to cause an abrupt termination of the coal seam at a rock wall. The coal seam may still be accessible, but the incline required to continue excavation through roof or floor rock may be dangerous for mining personnel, may make excavation time consuming, and may increase wear and tear on equipment (*18*). When the fault is too disruptive for mining to continue, large blocks of coal reserves must be abandoned because they cannot be mined safely or economically, requiring an unplanned retreat and unscheduled moving of equipment (*69*).

Even if large displacement is not an issue, the disruption of the roof rock is a problem in entries and intersections. Roof conditions are commonly unstable along a complementary fracture zone that parallels the strike of the fault (*58*). If fault planes intersect in the roof, blocks of rock can fall free after the coal is removed. Severe roof conditions, such as high roof falls that span the zone of disturbance flanking the faults, have been noted in association with faulted roof strata (*68*).

Faults also provide a conduit for water and gas flow. Even a minor fault formed by the regional tectonic forces intersects many different lithologic units within the coal-bearing sequence. When an aquifer is intersected, water can flow downward into the mine workings. If a number of coal seams occur in the stratigraphic sequence intersected by a fault, a large amount of methane can be liberated by the increased fracturing associated with the fault zone. Methane will migrate to fault planes, which offer low resistance to gas flow. When the fault zone is mined, increased concentrations of methane will be encountered, requiring extra ventilation. Unexpected pockets can result in explosions (*18, 69*).

Various impurities can be associated with fault zones that do not necessarily contribute to ground control problems but can degrade coal quality. Minerals such as calcite, clay minerals, quartz, and pyrite may be deposited along faults and fracture zones from water flowing along the fault planes. Gouge or breccia from a weak roof will be mined along with coal, increasing the ash content in that area. Zones of pulverized coal crushed by fault movement produce more dust than normal when mined (*69*).

Western U.S. coalfields exhibit mainly normal faulting, resulting from tensional tectonic forces. Related ground control problems range from minor to severe, depending on the spacing of the faults within the zone and the number of associated fractures. Thrust faults can be fairly common and present more of a hazard, because of fault planes splaying into additional planes, introducing more discontinuities to the roof strata. Because of the compressional forces that formed the thrust faults, more associated fractures and broken rock occur in the roof. Residual stresses still active in the roof further complicate the problem. Lateral shifting of strata during exploratory drilling and drilling of holes to install roof bolts can cause drill steel to be caught in the roof, and roof bolts can be sheared, leaving the section virtually unsupported, unless supplementary support has been installed as a precaution (*4*).

Recommendations for Roof Support

If it is possible to determine the exact location and the amount and direction of offset of the fault zone in advance of mining, ground control problems can be minimized before the fault is ever encountered (*68-69*). Mine plans can be adjusted to orient direction of mining through the fault in the most direct manner, minimizing the area of workings to be driven through fractured, unstable ground (*68-69*). Preparations can be made to excavate either the roof rock or the floor rock, depending on which unit is softer and easier to cut through based on previously conducted tests on drill cores. Mining height can be reduced in advance of intersecting the fault zone to avoid cutting any roof or floor rock if it is known that the amount of offset will allow it. If roof or floor rock must be excavated, gradually ramping upward or downward in advance of encountering the fault zone will minimize the change in slope required to access the coal on the other side of the fault and reduce effort required by mining personnel and equipment to negotiate a steep slope (*69*).

Roof control within a fault zone is complicated by the presence of complementary faults and fractures associated with the main fault. If the fault plane is at a low angle, angled bolts anchored in the hanging wall may stabilize the

roof. If there are closely spaced joints and fractures, supplementary support, such as straps, wire mesh, and in extreme cases, cribbing and posts, may be installed. Roof trusses may be needed if faults occur in intersections. If residual horizontal stresses that were unrelieved by fault formation still exist in the roof strata, they can cause lateral movement in the roof strata along bedding planes, shearing regular roof bolts. Stronger bolts, such as "super bolts," which are 2.5 cm in diameter, resin anchor combination bolts, or cable bolts are needed to reduce and withstand the effects of such lateral movements (*68*).

Predictive Techniques

Tectonic faults are usually detected by evidence observed through surface mapping. Unless the fault has a large enough exposure, such as a roadcut or a highwall, determining the amount of offset may be difficult from surface mapping. Projecting the location and offset from the surface exposure downward to the mine level can introduce some degree of error. Exploratory holes drilled down to the mine level near the fault zone can help determine a more exact location and degree of offset. Even drill holes are not exact if several faults occur within the zone. Seismic profiles can be helpful in delineating the number of discontinuities present if the offset of the strata is sufficient (*18, 69*).

Faults can be detected prior to mining by remote-sensing techniques. Faults often contain water and direct ground water to the surface. Increased vegetation or a change in vegetation type marks the trend of the fault. The fault can be a zone of weakness, easily eroded over time, producing a relative topographic low detectable on aerial photos or satellite images.

Observing the structure of the coal seam being mined can indicate the proximity of a fault zone. The orientation or spacing of the cleat is commonly changed or altogether destroyed near a fault zone. Coal may contain slickensides or shear zones within a fault zone (*10*).

CONCLUSIONS

The sedimentary and structural features discussed in this paper are frequently associated with roof instability in underground coal mines of both the Eastern and Western United States. The mechanisms that formed each feature are ordinary geologic processes; therefore, one or more of the features are related to nearly every documented coal seam. Careful geologic mapping of existing mine workings, documentation of roof instability problems encountered during mining, and a thorough exploration program prior to mine planning are the keys to anticipating and controlling instability in the mine roof. Knowledge of the features discussed in this paper enables early recognition of their existence in the roof strata, understanding of their effects on mining, and planning of methods to stabilize them successfully.

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GLOSSARY

anticline - folded strata in an archlike configuration.

authigenic - generated on the spot, formed in place.

axial plane - an imaginary plane intersecting a fold through the individual hingelines of all the folded strata.

basin - a syncline with a fold axis that plunges toward the center from two directions.

bedding-plane fault - relative movement between bedding planes induced by regional stress or subsidence of the depositional basin; also called bedding-plane slip.

bed load - soil, rock particles, and other debris rolled along the bottom of a stream by the current, but not suspended within the current.

boudinage - the breaking up of a stratum into small blocks by tensional deformation.

brackish water - water that has a saline content that is intermediate between that of fresh and sea water.

bump - a violent release of stresses built up in rocks surrounding a mine structure as a result of high overburden stress, tectonic stress, or mining-induced stress.

burst - a bump that also involves the violent expulsion of rock material.

calcareous - characterized by containing or being primarily composed of calcium carbonate.

carbonaceous - characterized by containing a large component of carbon.

cement - chemically precipitated material filling the interstices between grains of clastic rocks.

channel-lag deposit - coarse materials left as residual accumulation in the normal processes of a stream.

checkerboard roof - roof in which there is a high frequency of small roof falls and constant spalling, resulting from the presence of extensive fracturing; also called keystone roof.

clastic - consisting of fragments of rock or of organic structures that have been moved individually from their place of origin.

clastic dike - a tabular body of clastic material that has been injected into a fracture, joint, or other zone of weakness in a coal seam, mine roof, or floor.

clastic-dike fault - a nontectonic fault formed in association with a clastic dike.

clastic sill - a tabular body of clastic material that has been injected along a bedding plane or horizontal plane of weakness in a coal seam, mine roof, or floor; associated with depositionally controlled clastic dikes.

clay dike - a clastic dike filled with clay-sized material.

clay-dike fault - see clastic-dike fault.

clay seam - see clay dike.

clay vein - see clay dike.

cleat - a specialized system of joints occurring in coal oriented approximately normal to the bedding plane.

climbing ripple laminations - superimposed, undulating laminae built upward rather than offset in a forward direction.

concretion - isolated rock body of a composition chemically distinct from the surrounding lithologic unit.

conjugate shear joints - fractures or joints that form in a body of rock subjected to directional compressive force; they are usually oriented approximately 30° to the major axis of compression and form at an angle of about 60° to each other.

contemporaneous deposition - deposition of sediments occurring at the same time but under different environmental conditions.

crevasse splay - a tongue of sediment usually composed of thin, brittle beds of sandstone that are lobate to fan-shaped in areal extent, forming a wedge in cross section as it tapers laterally from the levee flanking a channel toward the adjacent flood plain.

crossbeds - internal bedding structures ranging in thickness from 5 cm to 2 m and oriented at an angle to horizontal bedding.

depositional environment - the characterizing conditions, including water depth, kinetic energy, and chemical conditions, under which sediments are deposited.

diagenesis - the process involving physical and chemical changes in unconsolidated sediment after deposition that converts it to consolidated rock.

differential compaction - relative change in thickness of mud and sandstone or limestone after burial due to reduction of pore space resulting from the load of overlying material.

dip joints - a geometric classification of joints that are parallel to direction of dip of bedding.

dip slip - movement along a fault plane parallel to the direction of dip of the fault plane.

dolomite - calcium-magnesium carbonate.

dome - an anticline with a doubly plunging fold axis.

drawslate - shale with a high coal content that crumbles easily; also called rashy shale.

epicontinental sea - shallow portions of the sea that lie upon a continental shelf, including portions that extend into the interior of the continent.

extension joints - a joint for which the shear component was zero so that shear stress at the moment of joint formation was in a direction normal to the joint face.

fabric - the orientation of components of a rock.

facies - the aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; especially as differentiating the unit from adjacent or associated units.

false drag - features, such as flexure of adjacent bedding, that indicate movement opposite to that of actual fault movement; also known as reverse drag.

fault - a planar discontinuity between blocks of rock that have been displaced relative to each other by tectonic forces acting regionally.

fault breccia - angular fragments in a matrix of finely ground rock found along a fault plane.

fault drag - features consisting of stratigraphic layers bending adjacent to the fault plane.

fault system - a number of fault zones of similar origin, but not necessarily similar orientation, occurring together.

fault zone - a number of faults of similar orientation occurring together.

fenster - a window of underlying rock exposed through the overlying thrust fault block.

fire clay - fine-grained, sometimes plastic, and often slickensided unit occurring immediately beneath a coal seam.

fissile - composed of very thin beds that separate easily.

fluvial - characterized by being produced by or associated with river processes.

fluviodeltaic - characterized by being produced by or associated with the interaction interface of river and oceanic processes at the site of a river delta.

fold - a bend or flexure in originally horizontal strata.

footwall - the block of rock lying below a fault or ore vein.

friable - easily crumbled, as with a sandstone held together by a weak cement.

fundamental joint system - the basic unit composed of two joint sets, one set systematic and the other nonsystematic, that are approximately orthogonal.

glide plane - a plane along which relative motion takes place in response to differential compaction.

goatsbeard - a fracture filled with gypsum or anhydrite precipitated by water seeping through the fracture.

gouge - pulverized rock of a claylike consistency formed by the grinding of rock during movement along the fault plane.

graben - a block of rock formed by tensional forces that has moved downward under the influence of gravity, forming a topographic low between two high-angle faults.

gradational contact - an indistinct boundary between two sediments of different chemical and physical composition that is characterized by a gradual intermixing of the two sediment types.

graded bedding - a type of stratification in which each stratum is composed of smaller grains than the stratum below it.

hanging wall - the block of rock lying above a fault or ore vein.

heave - the horizontal component of movement along a fault plane.

high-angle fault - a fault with a dip greater than 45°.

hillseam - stress-relief joints that have nearly vertical dip, oriented perpendicular to bedding, occur in shallow overburden where there is high topographic relief, tend to strike parallel to surface contours, and are believed to have formed as a result of local stress relief rather than from tectonic forces.

hingeline - an imaginary line drawn along the crest of a fold at the point where there is the smallest radius of curvature; also called fold axis.

horseback - a slab or wedge of roof rock separated from adjacent roof by intersecting slickensides.

horsebelly - see paleochannel.

horst - a relatively uplifted block between high-angle faults.

isopach - a line on a map drawn through points of equal thickness of a designated unit.

joint - an approximately planar discontinuity in a rock formed by brittle deformation with no displacement parallel to the plane.

joint set - a group of joints sharing the same genetic or geometric classification.

joint system - the sum total of all joint sets within a given area.

kettlebottom - mold and cast structure in which the form of a tree acted as a mold and was filled with clastic sediments that became the cast.

klippe - a remnant of an overlying thrust block surrounded by rock underlying the fault plane.

lag fault - normal fault dipping at less than 45°.

levee deposit - natural sediment buttresses deposited along a river channel bank by currents at flood stage.

limb - areas of a fold where there is a large radius of curvature extending outward from the hingeline.

lithic fragment - rock fragments composed of multiple minerals.

lithification - the process involving physical and chemical changes in unconsolidated sediment after deposition that converts it to consolidated rock.

lithology - the physical character of a rock unit based on grain size and mineralogic composition.

load cast - irregular bulges on a bedding plane formed by rapid deposition of sand on mud.

low-angle fault - a fault with a dip less than 45°.

marine bar - a submerged or emergent embankment of sand and gravel built on the seafloor by waves and current.

master joints - the larger, more prominent joints within a joint set.

monocline - a one-limbed flexure in strata that are otherwise flatlying except for the flexure itself, or a steplike bend in otherwise horizontal to gently dipping beds.

montmorillonite - a group of clay minerals characterized by swelling in water and extreme colloidal behavior.

mullion - parallel furrows along the fault plane that are more pronounced than slickensides.

mylonite - microbreccia that fills faults in wider zones of intense deformation.

net slip - a measurement of offset between two formerly contiguous points in the hanging wall and footwall of a fault.

nonsystematic joint set - a joint set within the fundamental joint system composed of less persistent parallel joints than the systematic joint set and formed later from the action of stress release.

nontectonic fault - a fracture formed by forces other than tectonic stresses, such as differential compaction of unconsolidated sediments or the sliding of large slump blocks, along which relative displacement or offset has occurred parallel to the fracture plane.

normal drag - features, such as flexure of adjacent bedding, that display movement in the same direction as fault movement.

normal fault - high-angle, primarily dip-slip fault in which the hanging wall has moved downward relative to the footwall.

oblique joints - a geometric classification of joints that are oriented at some angle to strike and dip of bedding.

oblique-slip fault - a fault in which the strike-slip and dip-slip components are of nearly equal magnitude.

overbank deposit - sediments deposited adjacent to the main river channel by currents at flood stage.

paleochannel - a laterally discontinuous lithologic unit consisting of younger or contemporaneous sediments that have intersected underlying or adjacent sediments by the erosional action of an ancient stream. Also known as want, roll, horse belly, and sand or sandstone channel.

paleocurrent - the current that flowed in ancient river systems.

paleoslumps - remnants of soft-sediment deformation that formed either by differential compaction or when steep channel banks accumulated a sediment load that eventually became unstable and slid down into the deeper portions of the channel under the influence of gravity.

pinchout - the abrupt termination of a stratum.

pug - soft microbreccia found along a fault plane.

quartz arenite - a sandstone lithology composed of 90 to 100 pct quartz grains cemented by quartz.

radial joints - nonparallel joints that are oriented approximately perpendicular to bedding within folded strata.

recumbent fold - a fold in which the axial plane is more or less horizontal.

regression - gradual contraction of a shallow sea resulting in the emergence of land, as when sea level falls or land rises.

release joints - a secondary joint set oriented parallel to the regional major axis of compression, formed by release or relaxation of compressional forces.

reverse fault - a high-angle, primarily dip-slip fault in which the hanging wall has moved up relative to the footwall.

ripple marks - asymmetrical undulations along a bedding plane formed in unconsolidated sediment by the action of current.

rock spar - see clastic dike.

roll - see paleochannel.

rooted clay - a weak clay unit that served as a substratum for vegetation and, therefore, contains fossil roots and disrupted bedding from root action.

sandstone channel - see paleochannel.

scour-and-fill features - small asymmetrical troughs in the substratum filled with a different sediment type.

sedimentary dike - see clastic dike.

shear joints - a genetic classification of joints formed with some nonzero component of shear stress present in the local stress field during joint formation.

shear plane - see glide plane.

shear zone - an area where relative offset between blocks of rocks has occurred owing to tectonic forces acting regionally; similar to a fault zone except that no distinct fault planes can be detected because the local deformation is ductile.

slacking or slaking - deterioration of a rock unit, usually of high clay content, upon exposure to mine atmosphere.

slickensides - curved surfaces that are grooved and striated, but otherwise polished smooth by relative movement across the slickenside surface.

slip plane - see glide plane.

soft-sediment deformation - displacement or distortion of sediments before they are lithified.

spar - see clastic dike.

stack rock - sandstone comprised of thin beds that separate easily; also called flaggy sandstone.

stratigraphy - the layers of discrete sediments or rock units distinguished by any of the characteristics, properties, or attributes that rocks may possess, including lithology, fossil content, and age.

strike joints - a geometric classification of joints that are parallel to direction of strike of bedding.

strike slip - movement along a fault plane parallel to the strike of the plane.

strike-slip fault - high-angle fault along which movement has occurred parallel to strike rather than dip; also called transcurrent or wrench fault.

syncline - folded strata in a U-shaped configuration.

systematic joint set - the joint set within the fundamental joint system, composed of strong, parallel joints, that intersects all other joint sets, shows greatest vertical persistence, and formed perpendicular to the regional axis of least compression.

tectonic - related to regional stresses caused by large-scale geologic processes such as upwelling of magma, which causes tensional tectonic stresses, or continental plate collision, which causes compressional tectonic stresses.

tensional joints - a genetic classification of joints that were developed in a tensional stress regime, forming parallel to the major axis of regional compression.

throw - the vertical component of movement or dip separation along a fault plane.

thrust fault - a low-angle reverse fault in which reverse movement is inferred rather than supported by direct evidence.

transcurrent fault - see strike-slip fault.

transgression - gradual expansion of a shallow sea resulting in the progressive submergence of land, as when sea level rises or land subsides.

want - see paleochannel.

washout - a paleochannel that has partly or totally cut through the coalbed.

wrench fault - see strike-slip fault.

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