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Information Circular 8976

Geologic Factors in Coal Mine Roof Stability—A Progress Report

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UNITED STATES DEPARTMENT OF THE INTERIOR
William P. Clark, Secretary

BUREAU OF MINES
Robert C. Horton, Director

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Library of Congress Cataloging in Publication Data:

Moebs, Noel N

Geologic factors in coal mine roof stability.

(Information circular ; 8976)

Bibliography: p. 25-27.

Supt. of Docs. no.: I 28.27:8976.

1. Coal mines and mining—Safety measures. 2. Mine roof control. 3. Coal—Geology. I. Stateham, Raymond M. II. Title. III. Series: Information circular (United States. Bureau of Mines) ; 8976.

TN295.U4 622s [622'.334] 84-600018

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°F	degree Fahrenheit	µin/in	microinch per inch
ft	foot	pct	percent
h	hour	psi	pound (force) per square inch
mi	mile	yr	year
min	minute		

GEOLOGIC FACTORS IN COAL MINE ROOF STABILITY–A PROGRESS REPORT

By Noel N. Moebs [1] and Raymond M. Stateham [2]

ABSTRACT

This report summarizes 10 selected Bureau of Mines research contract reports produced from 1970 to 1980 which consist largely of geologic studies of coal mine roof support problems. Significant highlights from the contract final reports are discussed and presented in practical terms. The selected reports focus on the Appalachian and Illinois coal mining regions.

In the Appalachian coal region, two geologic structures, roof rolls and slickensides, predominate over all structures as features that directly contribute to roof falls. Studies of these and other structures are reviewed, and improved methods of utilizing drill core and core logs to prepare hazard maps are presented. Among the reports described are several on the weakening effects of moisture on shale roof, as determined from both laboratory and underground measurements, and an assessment of air tempering as a humidity-control method. Also summarized are findings concerning the time lapse between roof exposure and permanent support installation as a factor in the effectiveness of roof bolting.

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INTRODUCTION

Instability in coal mine roofs is considered to be the result of one or both of two basic types of causative factors--defect-related and/or non-defect-related. Defect-related causes are geologic by definition because they are related to naturally occurring features in the rock mass around the mine opening. Non-defect-related conditions can be described by one word--stress. The stress exists because of geostatic pressure, regional or local geologic conditions, or the creation of the mine opening. This report deals with several investigations of defect-related geologic factors and their contributions to instability in coal mine roofs. It is anticipated that a better understanding of geologic phenomena such as structure and lithology as contributing factors to instability will lead to a keener insight into the causes of roof falls. This better understanding should also lead to improved methods of roof support, and techniques for the prediction and classification of potentially unstable roof in advance of mining. Consequently, the Bureau of Mines is identifying and describing geologic features that contribute to roof instability, through research grants and contracts with educational and consulting organizations and through the work of Bureau researchers working in cooperating mines.

The emphasis in this summary report is on contract reports written since 1970, when the Bureau renewed its efforts to resolve the interrelation between geology and roof conditions. Reports from other sources are cited where pertinent. It is hoped that this annotated summary will provide mine engineers and geologists with useful information which otherwise might remain obscured in technical reports that do not receive wide circulation. Although this review of geologic studies concentrates on the Appalachian and Illinois coal mining regions, some topics discussed might be applied to other localities as well. It is also hoped that this report will encourage more mining companies to document geologic features in active mines and in zones where unusually heavy support is required.

The urgent need to use all available means to deal with roof support problems is made clear by the recurring accidents that result from roof falls. These accidents result in fatalities, injuries, and costs to operations in terms of lost labor time, compensation, delays, cleanup, and repairs. Up to and including 1937, roof falls accounted for about 45 pct of the total number of fatalities in underground coal mines (14)[3] and in 1970 roof falls still accounted for 41 pct of the fatalities. In 1977, a total of 1,420 injuries from roof falls was reported to the Mine Safety and Health Administration (MSHA), of which 30 were fatal. The following tabulation of total fatalities from roof falls for recent years shows that this hazard continues to constitute a serious problem in coal mines:

1978..................	33
1979..................	65
1980..................	32
1981..................	41
1982..................	52

Falls in which there is no injury are innumerable. These falls commonly block haulageways or air courses and damage track, cables, and conveyor belts. The geologic studies reviewed in this report are part of a renewed effort toward advancing the technology needed to make coal mining safer and more productive through improved roof control.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

BACKGROUND

EARLY INVESTIGATIONS OF COAL MINE ROOF INSTABILITY

The problem of coal mine roof support has been the object of numerous investigations in the United States since early in the 20th century. A Bureau of Mines report (14) on roof movement in coal mines lists 62 references published between 1912 and 1937. In that report, however, a failure of coal mine roof was commonly described and explained in the context of a particular locality or hypothetical case. This practice has been continued to the present, with the geologic environment receiving little attention. Unfortunately, emphasis upon the unique nature of a roof fall has made it difficult to isolate common causes of roof instability, and the role of specific geologic phenomena is little understood. Meanwhile, roof failure continues to be the major hazard in underground mining.

Since 1930, great advances have been made in the field of rock mechanics and coal mine roof support technology, as summarized by Adler and Sun (1). A study reported by the Bureau in 1941 (15) concerned the effect of moisture on mine roof disintegration.

GEOLOGIC APPROACHES

The first significant report on the geologic characteristics of coal mine roof rock in the Eastern United States was not published until 1948 when Holland (17) described his observations for the West Virginia Coal Mining Institute. This was followed shortly by a somewhat more detailed discussion by Price (25) on roof rock geology and its influence on selecting types of roof support. From 1960 to 1972, publications dealing with geologic features that affect coal mine roof stability appeared in greater numbers. These include three of special significance for their contributions to the understanding of roof support problems. In the first, by Diessel and Moelle (8), sedimentary and structural features in Australian floor and roof strata were analyzed to determine their influence on the stability of mine openings, and the methods used to analyze these features were outlined. Diessel and Moelle concluded that both sedimentary and structural analyses were useful in planning future workings of a mine because the analyses could be used to establish the trends of troublesome geologic structures such as faults, washouts, and rolls.

The second contribution of special significance was by Weir (34). Although brief, it is an excellent summary of geologic conditions and related roof falls encountered in Sullivan County, IN. Weir's conclusions, which caution against oversight of geologic detail, are worthy of quoting in their entirety:

> In evaluating roof rock conditions, the geologist must look at the rocks from many viewpoints. No single physical or chemical parameter tells the whole story. Not only are the lateral variations in the rocks important but vertical variations are also. Not only may the rock be significantly different from one foot to the next but, in some cases, from one centimeter to the next.
>
> Lithology and thickness of beds, jointing, strength of bedding plane bond, and the effect of moisture are important considerations. No single criterion seems to be adequate for practical roof evaluation.

In the third significant publication, Dahl and Parsons (7) combined finite-element stress analysis with a conventional examination of geologic factors affecting roof fall severity. They emphasized the importance of the geometry of a situation, room width, and residual compressive ground stresses.

An additional publication edited by Donaldson (9), appearing in 1969 for use as a guidebook, is a comprehensive description of the formation of the Permo-Carboniferous rocks in the Appalachian Basin; it contains abundant information directly applicable to coal mining and exploration. Also included are several separate sections in which the geologic setting, as specifically related to roof rock conditions, is discussed. More recently, Overbey (24) described procedures for constructing a hazard-potential map using a wide range of geologic features which have been cited as contributing factors in roof falls. In 1975, McCulloch, Diamond, Bench, and Deul (20) reviewed geologic factors affecting mining of the Pittburgh Coalbed; and in 1979, Stahl (29) similarly described geologic features affecting coal mine roof in general.

The Bureau has been actively and continuously investigating coal mine roof instability since it was established in 1910 (14) and has issued numerous technical and educational papers on improving methods of roof support. However, the factor of geologic variables and their bearing on the effectiveness of roof stability has not been fully appreciated until recently, and techniques for analyzing these variables are only now emerging. It is at this stage that the Bureau is attempting to screen the numerous geologic investigations to identify those that seem to have the greatest potential for application to the study and prevention of coal mine roof failure. Among the more promising geologic approaches are the conventional ones used in several of the reported contract studies whereby roof falls are related to mappable geologic features.

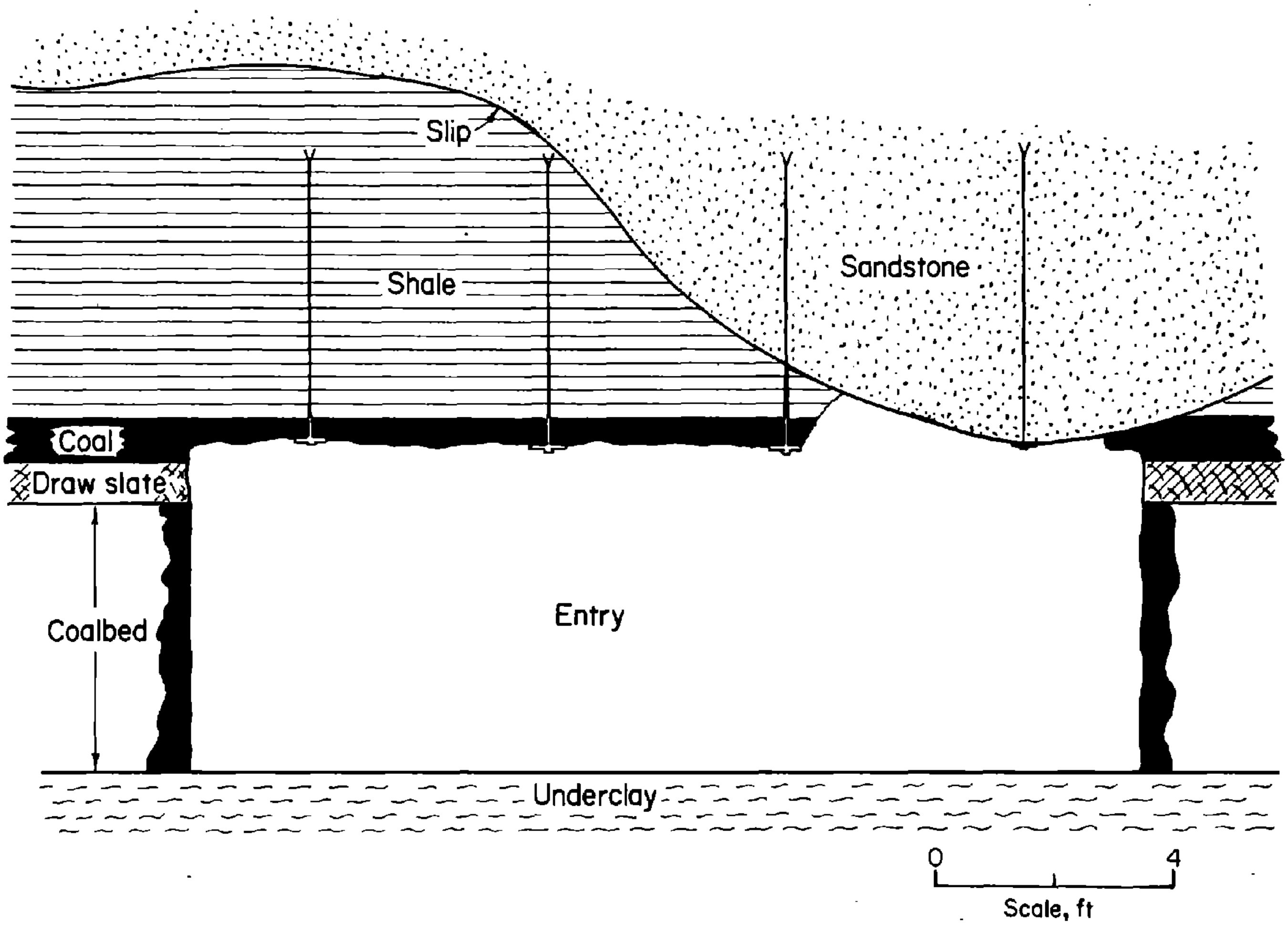

FIGURE 1. - Sandstone-filled paleochannel or roof roll.

RECENT BUREAU STUDIES

Beginning about 1970, the Bureau renewed its efforts to identify the geologic factors that contribute significantly to roof failure. The initial effort consisted of an investigation of roof falls in the northern portion of the Pittsburgh Coalbed in southwestern Pennsylvania and northern West Virginia. This work included numerous interviews with operating personnel and examination of the roof in virtually every major mine in the study area. Based on these activities and analyses of roof fall maps, it was concluded that the incidence of falls was significantly higher beneath stream valleys, in close proximity to paleochannels (fig. 1), clay veins (fig. 2) and other small-scale geologic features, and wherever large slickensides (fig. 3) occurred in the roof strata. Falls also commonly occurred where roof rock consisted of weak claystones or laminated sandstone. Broad gentle folds, characteristic of the Allegheny Plateau, showed no relation to roof fall zones. These results confirmed that geologic features contribute significantly to roof failure and should be studied in greater detail. Therefore, the Bureau awarded research contracts covering a variety of approaches to the problem of roof failure. Although the geologic studies dominated, studies of interrelated engineering and mining conditions were included in these investigations. In several instances where the investigation began as an engineering-type study, the geologic conditions soon emerged as the dominating factor.

From 1970 to 1980, 10 research contracts were awarded by the Bureau in which the role of geology in roof failure was the main theme. In the following sections of this paper, the significant findings of these contracts are reviewed, and the results of relevant research conducted by the Bureau are also cited. Because of the widely divergent and sometimes interrelated topics included in these contracts, any attempt at strict classification would be futile. However, the contract studies are grouped here

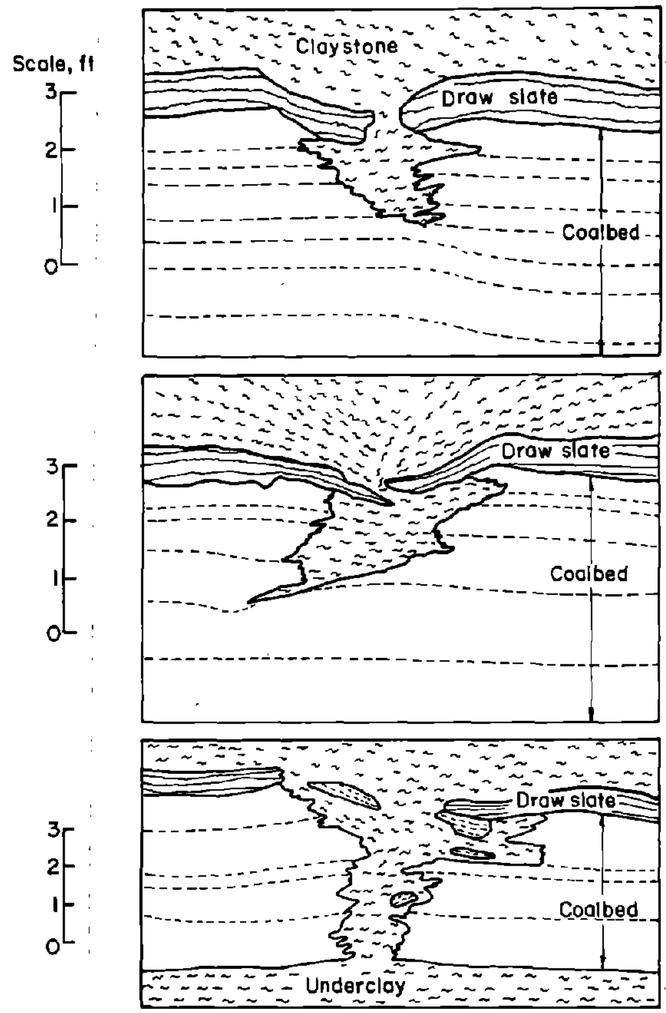

FIGURE 2. - Common forms of clay veins or clay dikes.

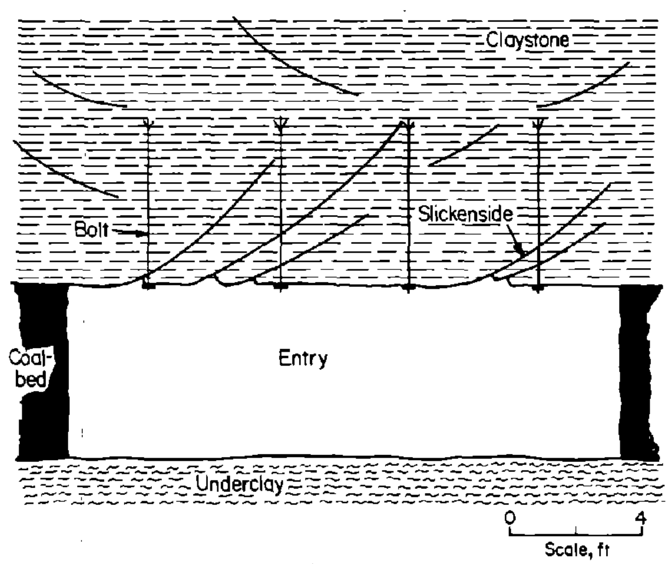

FIGURE 3. - Slickensides in claystone roof strata.

into two broad categories: those dealing primarily with the structural and lithologic character of mine roof rock and those relating to physical properties of roof rock, including changes in these properties upon exposure.

The complete texts of these contract reports can be examined at Bureau libraries where they are held on open file,[4] or copies can be purchased from the National Technical Information Service (NTIS), Springfield, VA 22161.

REVIEW OF CONTRACT RESEARCH ON THE STRUCTURAL AND LITHOLOGIC CHARACTER OF COAL MINE ROOF ROCK

DEVELOPING GEOLOGICAL STRUCTURAL CRITERIA FOR PREDICTING UNSTABLE MINE ROOF ROCKS, CONTRACT H0133018 (18)

This study was designed to identify and describe the geologic structures related to roof falls in the Highsplint and Bailey Creek Mines in eastern Kentucky. The main objective was to develop methods for predicting and classifying roof conditions on the basis of geologic studies.

Both mines are located in Harlan County about 1.5 mi east of the Pine Mountain thrust fault and in the Darby and Harlan Coalbeds of the overthrust block. Depth of overburden ranges from near zero to 1,500 ft beneath mountain tops. Neither mine had been core drilled; therefore, the investigation was conducted largely by detailed underground mapping and sampling, followed by laboratory studies of roof rock samples, examination of limited outcrop exposures, and joint analysis.

Significant Findings

Field studies showed that roof support problems in the Highsplint Mine (Darby Coalbed) were related to either of two geologic conditions. The first was large rolls, or undulations, in the basal contact of thick sandstone (fig. 4) occurring within 15 ft of the roof and truncating the horizontal shale strata, with intensely slickensided shale close to the rolls. The second condition was mine roof which consisted (in the first few feet) of lenticular, thinly interlaminated, poorly bonded sandstones and shale (fig. 5). The rolls were U-shaped, strongly linear, and about 20 ft wide. The interval of roof rock between the coalbed and the main sandstone roof ranged from 0 to 15 ft due to the rolling, or undulatory, basal contact of the sandstone. The rider coal was often replaced by the sandstone. Jointing in the main sandstone roof was not a major factor in roof failure.

At the Highsplint Mine, the directional trends of the major sandstone roof rolls were established by underground mapping and successfully projected from one set of mine entries to another, over distances that ranged from 400 to almost 2,000 ft. Projection of the geologic trends was facilitated by classification of mine entry roof according to four predominant geologic conditions, as follows:

1. Laminated shale with diagonal slickensides.

2. Laminated shale with horizontal or low-angle slickensides.

3. Rolling base of thick sandstone above roof level, with intervening shale between rolls.

4. Rolling sandstone at roof level.

Through examination of the coalbed and roof rock exposed along the crop line surrounding a portion of the mine, it was established that if well-defined sandstone rolls could be detected in outcrop, roof problems related to the rolls could be expected to occur in the mine.

In contrast, roof failure in the Bailey Creek Mine (Harlan Coalbed) was attributed to lenses of rippled, cross bedded, and flaggy laminated sandstone that cut across the shale roof strata. These

[4]Libraries are located at Bureau facilities in various cities. Not all open file reports are available at all libraries.

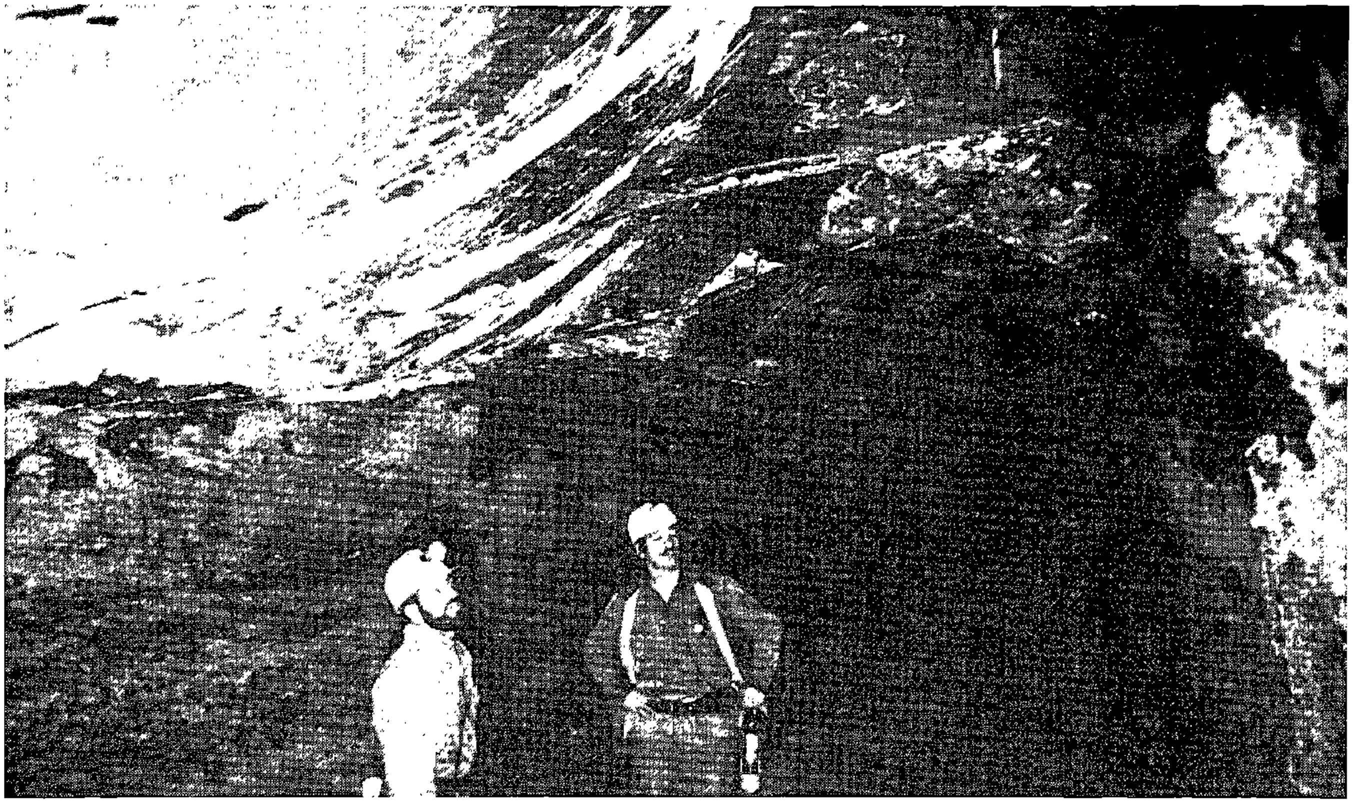

FIGURE 4. - Roof roll with heavily slickensided margins.

FIGURE 5. - Thinly interlaminated, poorly bonded sandstone, shale, and coal roof strata.

lenses ranged from 60 to 100 ft wide and are probably flood plain splays. Roof falls commonly extended 12 to 15 ft upward to the rider coal. The occurrence of roof cutters or shears at the intersection of roof and rib indicated that high stresses were responsible for some roof failure. Also, some joint-related falls occurred near the crop line and beneath some stream valleys where the overburden was 200 ft or less. The preferred direction of jointing under shallow cover was used to plan a proposed set of entries in order to minimize the detrimental effects of driving parallel to closely spaced jointing.

A study was also conducted on the use of Landsat (satellite) imagery for the detection of linear zones of structural weakness that might contribute to unstable roof conditions. It was concluded that Landsat imagery provides a rapid and accurate means of determining the location and trend of major geologic structures. It also helped in tracing significant structures from one mine to another. In the northern West Virginia area of the Dunkard Basin, the study showed a close correlation of Ronchi grating directions and the roof fall zones occurring under stream valleys, commonly a north-south trend. This suggests that in situ stresses are an important factor in this mode of failure.

Comment

A major effort in terms of worker-hours was expended in mapping the character and trend of rolls, sandstone channels, and fractures in main roof that were causally related to roof falls. Projections of these geologic features were used to identify potentially hazardous zones, and new development was planned to avoid these zones wherever possible. Because of the discontinuous and erratic nature of most roof structures, projections beyond a few hundred to a thousand feet are unreliable. However, mapping of well-defined linear roof structures may be sufficently simplified that an occasional underground visit by a geologist will be adequate to record the structures on operations maps and serve as an aid in laying out development.

The classification of roof areas devised in this study requires some geologic expertise, but the technique aids in mapping trends of roof structures and may prove useful in determining the probable support requirements in areas to be mined.

A simplified method was devised in which Landsat film transparencies were used for direct plotting of lineaments to scale for correlation with surface and subsurface data. The method proved useful in tracing structures from one mine to another.

METHODS AND CRITERIA FOR PRODUCING A PHOTOGRAPHIC CORE LOGGING MANUAL FOR THE PITTSBURGH BASIN, CONTRACT J0188115 (13)

The purpose of this contract was to develop and produce a field guidebook for the identification and classification of cored roof rock in the northern Appalachian bituminous coal region. The specific objective was to provide drillers, engineers, and geologists with the means to standardize the identification of core roof rock so that drill-core data can be more fully utilized in mine planning and ground control. Drill-core data can be applied to mapping areas of potentially bad roof conditions, determining optimum roof support methods, and establishing the continuity of a coalbed.

Preparation of the guidebook was accomplished by collecting, sorting, classifying, and photographing numerous samples of core from throughout the northern Appalachian coal region. Representative core samples for each of the major rock types were photographed in color both in wet and dry condition. A descriptive key was developed for each major rock type and referenced to the appropriate color photographs for ease in identifying core samples. Code numbers were assigned to each rock type for the purpose of computer storage, manipulation, and retrieval of data. The guidebook is softbound, printed on weatherproof paper, and measures 5-1/2 by 8-1/2 in.

The same contractor (University of South Carolina) produced a similar guidebook under Bureau contract H0230028 (12) for cored rocks from the Pocahontas Basin in southern West Virginia, eastern Kentucky, and southwestern Virginia.

Significant Findings

The preparation of this drill-core guidebook demonstrated that a practical system of standardized classification can be developed even in regions where coal measure rocks are commonly gradational both vertically and laterally.

Comment

Adequate exploratory drill-core identification is fundamental to sound geologic analysis of the core log data. The preparation of isopach maps, geologic sections, coal reserve maps, and mine layouts depends on the availability of properly classified drill-core data, which can be achieved through the use of this guidebook.

The major rock types illustrated and described in the guidebook can be easily recognized by the core driller or geologist; so in all drill-core logs based on this system, the rock nomenclature will be standard. Thus, drill core logged by different individuals should be classified identically and should be fully comparable.

Standardized classification and coding of drill core is especially essential for the successful use of computer-generated maps of various types; such maps are rapidly gaining in popularity and are easily obtained once precise drill-hole data are acquired. Once the process of computer map generation has begun, however, the judgment of the geologist is not utilized until completion.

A STUDY OF ROOF FALLS IN UNDERGROUND MINES, CONTRACT H0230028 (12)

The objective of this study was to identify the major geologic features occurring in mine roof that lead to roof failure. In particular, the purpose was to establish through statistically valid analysis specific rock types, structures, rock sequences, or other attributes that relate to roof quality. The investigation was performed over a period of 4 yr in the Pocahontas No. 3 Coalbed of southern West Virginia and southwestern Virginia.

Five operating underground mines were selected for detailed study. In each mine, investigators documented geologic factors in the roof that related to roof falls. The mines were selected on the basis of statistical analyses of the range in variation in mining conditions, roof conditions, and geologic phenomena. Within each mine, roof characteristics were documented in areas designated as good and bad roof according to stability.

The sequence and lateral distribution of roof rock types were determined from drill-core records. Roof structures were identified and mapped in each mine. Mining practices related to roof support were documented.

The study concluded with quantitative determinations of (1) the specific rock types, sequences, structures, and characteristics, that correlated directly with roof quality and (2) the extent of rocks having certain roof attributes.

During the part of the study in which drill core and drill-core logs were analyzed, it became evident that an improved method of core identification and logging was necessary to assure uniform use of rock nomenclature. Therefore, a prototype field guidebook was developed to facilitate logging and classification; it included a key to rock types and color photographs of drill core. (The guidebook developed for this study was the prototype for the drill-core guidebook described in the preceding section.)

Significant Findings

As a result of this investigation, several relationships between roof quality and roof rock became relatively clear; these relationships are listed below.

1. Thick shale--that is, a solid mass of shale occupying the entire 40 ft above the top of the coalbed--produces the best quality and most stable roof.

2. Thick sandstone--that is, a solid or nearly solid mass of sandstone occupying the entire 40 ft above the top of the coalbed--may produce either good or bad roof. Poor roof occurs when shale, ironstone pebbles, coal stringers, or crossbedding are abundant in the lower 3 or 4 ft of the sandstone.

3. Low splay sandstone (within 8 ft above the top of the coalbed; figure 6) and high splay sandstone (8 to 30 ft above the top of the coalbed) may produce either good or bad roof conditions, depending on other factors.

4. Roof strata that become more coarsely grained upward, as in a shale-sandy shale-sandstone sequence, produce excellent roof when the entire sequence is about 30 or more feet thick.

5. Various types of claystone, commonly known as fire clay, seat earth, clod rock, or underclay, are among the poorest quality roof materials when they are massive and unlaminated.

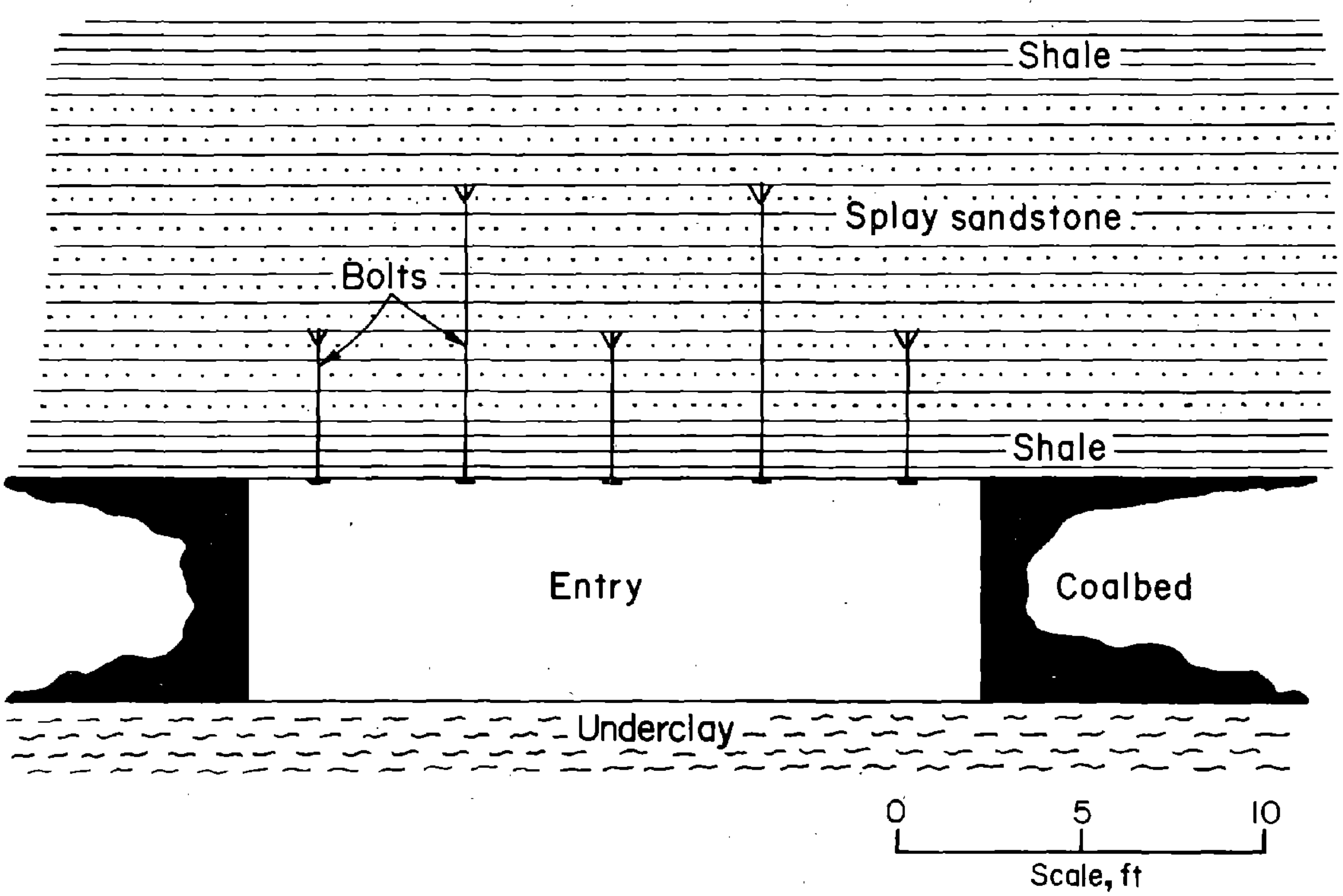

FIGURE 6. - Low splay sandstone zone in mine roof.

6. Slickensided rock produces the worst roof problems. Slickensided structures form as shear planes in a number of different rock types and geologic settings, but are most commonly found in claystone, at the contact between channel-scour sandstones and shale, and surrounding kettlebottoms and strongly inclined slump deposits.

Comment

The importance of this work lies in the systematic manner in which various types of roof were categorized and related to roof competence. The six basic types of roof described above can be recognized in accurately prepared drill-core logs, thus enabling the engineer or geologist to block out reserve areas according to anticipated roof competence and probable method of optimum roof support. The precision of this method of roof assessment rests largely on the spacing of exploratory drill holes.

The prototype guidebook to cored rock made it possible to accurately identify and classify the roof strata.

PREMINING IDENTIFICATION OF HAZARDS ASSOCIATED WITH COAL MINE ROOF MEASURES, CONTRACT J0177038 (33)

The objective of this contract was to summarize in a graphic manner (on maps) all rock fall hazards related to geologic conditions in the Pittsburgh Coalbed for a nine-county area centering around the northern panhandle of West Virginia. The mapped area included portions of eastern Ohio, northern West Virginia, and southwestern Pennsylvania.

The study continued for about 18 months and was divided into two phases. Phase 1 included data collection from drill-core logs, mine maps, interviews, roof fall reports, published technical reports, and mine visits. Statistical analysis of the data was used to identify 12 geologic and mining variables that are causally related to hazardous roof conditions, and a hazard-classification system was developed for use in preparing hazard zone maps. Each variable was weighted in terms of potential roof fall occurrence and severity.

In phase 2, a series of overlay maps on a scale of 1:62,500 was compiled, illustrating the occurrence of geologic variables; and a composite hazard zone map was generated by machine processing and integration of the variables. All maps were bound into five separate folios 28- by 36-in indexed by county. The maps were developed using methods that facilitate user modification as more site-specific information becomes available or when selected variables are weighted in different order. A final technical report and map users' guide were written to accompany the folio.

Significant Findings

The systematic collection and analysis of field data resulted in the identification of seven geologic and five mining variables causally related to roof failure. The five mining variables and four of the geologic variables were either inappropriate for graphic representation or insufficiently detailed for delineation on a hazard zone map. Only 3 of the significant geologic variables--overburden thickness, roof lithology, and vertical distance to the rider coal--were useful in final map preparation; these variables were divided into 12 categories. Each variable was weighted and compared in a risk-interaction matrix, and final values were categorized into high- , moderate- , and low-risk designations.

A separate transparent overlay map on a scale of 1:62,500 was prepared for each category. Ten categories were based chiefly on the lithologic character of roof rock at various levels above the coalbed, one was based on structure, and one was based on overburden thickness. A final hazard zone map (fig. 7) was produced by combining 4 of the 12 categories after the weighting factors for probability and severity of the parameters were adjusted.

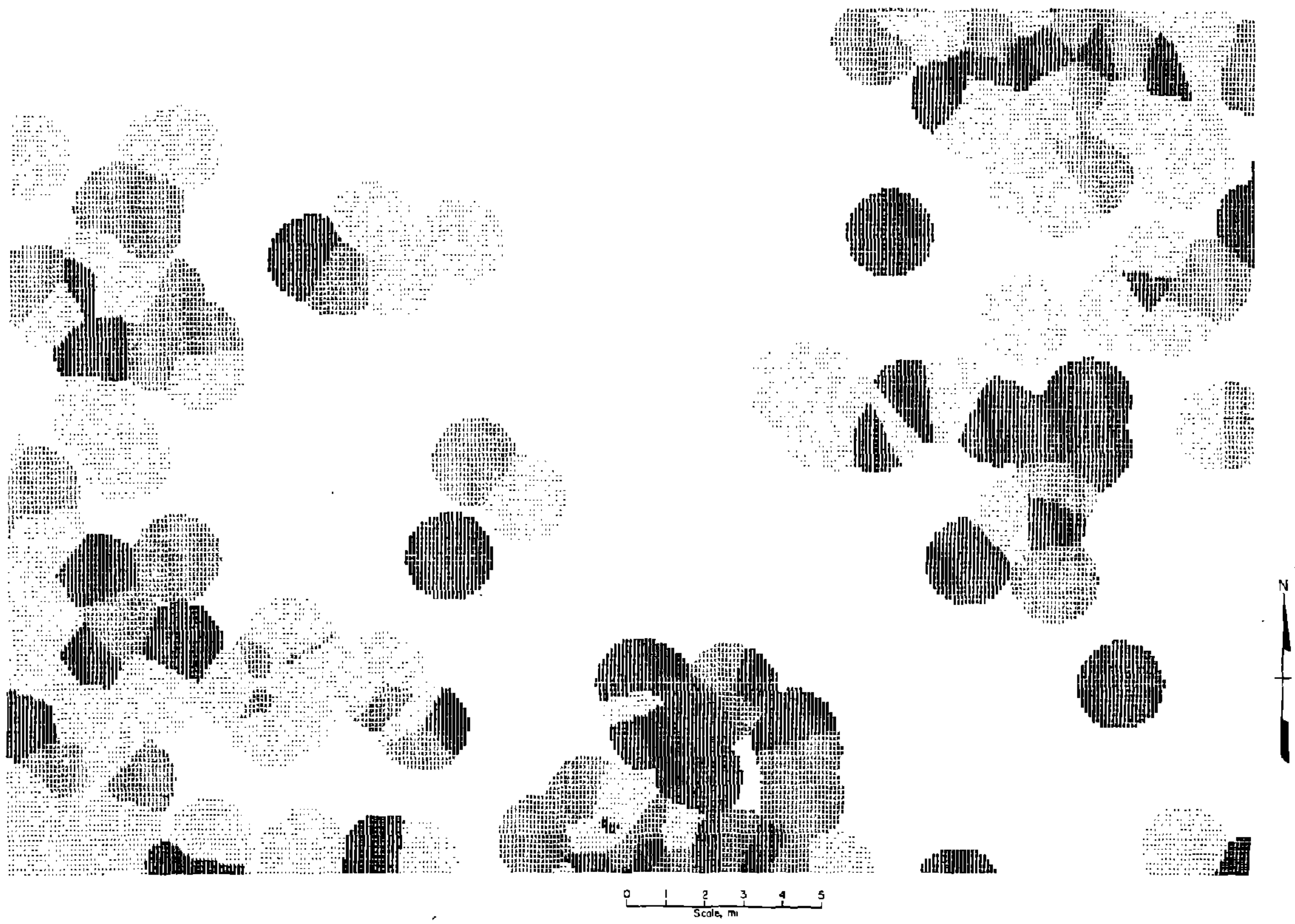

FIGURE 7. - Composite hazard zone map (33). Darkest areas indicate zones of highest risk. (The search radius for each data point (drill hole) was restricted to 1 mi.)

Comment

The overlay maps illustrating the 12 geologic variables and the final hazard zone map representing an integration of several of these variables were conceived as a set of working maps that could be revised as additional detail is acquired through core drilling, mine development, or geologic studies. To facilitate the preparation and revision of such maps, the contractor prepared an explanatory text that describes in detail a computer program for data analysis and map printout. This test also includes instructions for inputting additional drill log data into the system for revision of the hazard maps. However, not all geologic variables can be programmed for computer analysis; some hazard risk zones must be developed manually through the use of overlays and geologic judgment. The success rate in predicting roof failure using the method developed in this study is undetermined and will require considerable site-specific experimentation to resolve.

ENGINEERING STUDY OF STRUCTURAL GEOLOGIC FEATURES OF HERRIN (NO. 6) COAL AND ASSOCIATED ROCK IN ILLINOIS, CONTRACT H0242017 (19)

This investigation summarized all existing knowledge of the influence of the geologic fabric of roof strata on roof stability in mines in the Herrin (No. 6) Coalbed in Illinois. Conducted over a 4-1/2-yr period, the investigation included underground work in operating mines and a systematic compilation of existing information on file with the Illinois State Geological Survey. The geology of the Herrin roof rock was described in detail, and numerous structural and stratigraphic features were identified and related to roof conditions.

Significant Findings

The roof of the Herrin Coalbed consists of two major rock types: gray shale and black shale which in places includes a limestone bed. About 90 pct of the coalbed is overlain by the black shale, but the distribution patterns of the two rock types are intricate, irregular, and patchy. The position and thickness of the limestone member of the black shale is also variable. Sandstone is occasionally encountered in the roof.

Commonly, mines in the Herrin Coalbed that have the most severe roof support problems have a gray shale roof. The problems are caused by roof rolls, a protrusion of the shale material into the upper portion of the coalbed (fig. 8). The rolls are usually accompanied by numerous slickensides or shear planes and thin coal stringers. The origin of these rolls is attributed to differential compaction and deformation of the sediments while they were still in a plastic water-laden condition.

Roof of the black-shale type is generally stable where the shale is very thick or where the limestone member is at least 2 ft thick.

Roof consisting of laminated sandstone beds is difficult to support because the bedding surfaces are coated with plant material or mica which allows individual layers to separate and sag or fall.

Roof support problems were occasionally encountered where claystone dikes with highly slickensided boundaries interrupted the continuity of the shale roof (fig. 9). The dikes were most common where the limestone member of the black-shale group formed the immediate roof. These claystone dikes (or clay veins, in miners' terms) are irregularly shaped bodies of claystone that partially or completely transect the coalbed and extend into the roof. The claystone softens after prolonged exposure to humid mine air, adding to the support problem; and the slickensided dike is so poorly bonded to adjacent roof strata that the rock begins to fall when the supporting coal is removed--oftentimes before artificial support of any kind can be established.

Joints occurring in mine roof were correlated with minor slabbing of immediate roof but were not a cause of major roof falls.

The individual geologic features or conditions described above all contributed to roof failure, but most of them were too small and too variable to be recognized or predicted entirely by means of normally spaced exploratory drill holes. Even major faults were difficult to recognize in widely spaced drilling. However, core drilling provided a general indication of the roof character and variability likely to be encountered during mining.

Comment

This study clearly showed that innumerable and highly variable small-scale geologic features cause the major roof support problems for mines in the Herrin Coalbed. Roof rock types, as well as individual geologic features, are highly irregular in occurrence. Because of this, normally spaced core drilling alone can provide only the most general and imprecise information; usually the information is not adequate to delineate potentially hazardous zones. It is therefore particularly important to use close spacing during exploratory core drilling and to revise assessments or predictions of roof conditions as soon as underground data begin to emerge from development work. An underground mapping program to permanently record easily recognized roof structures will provide the necessary data for revised predictions.

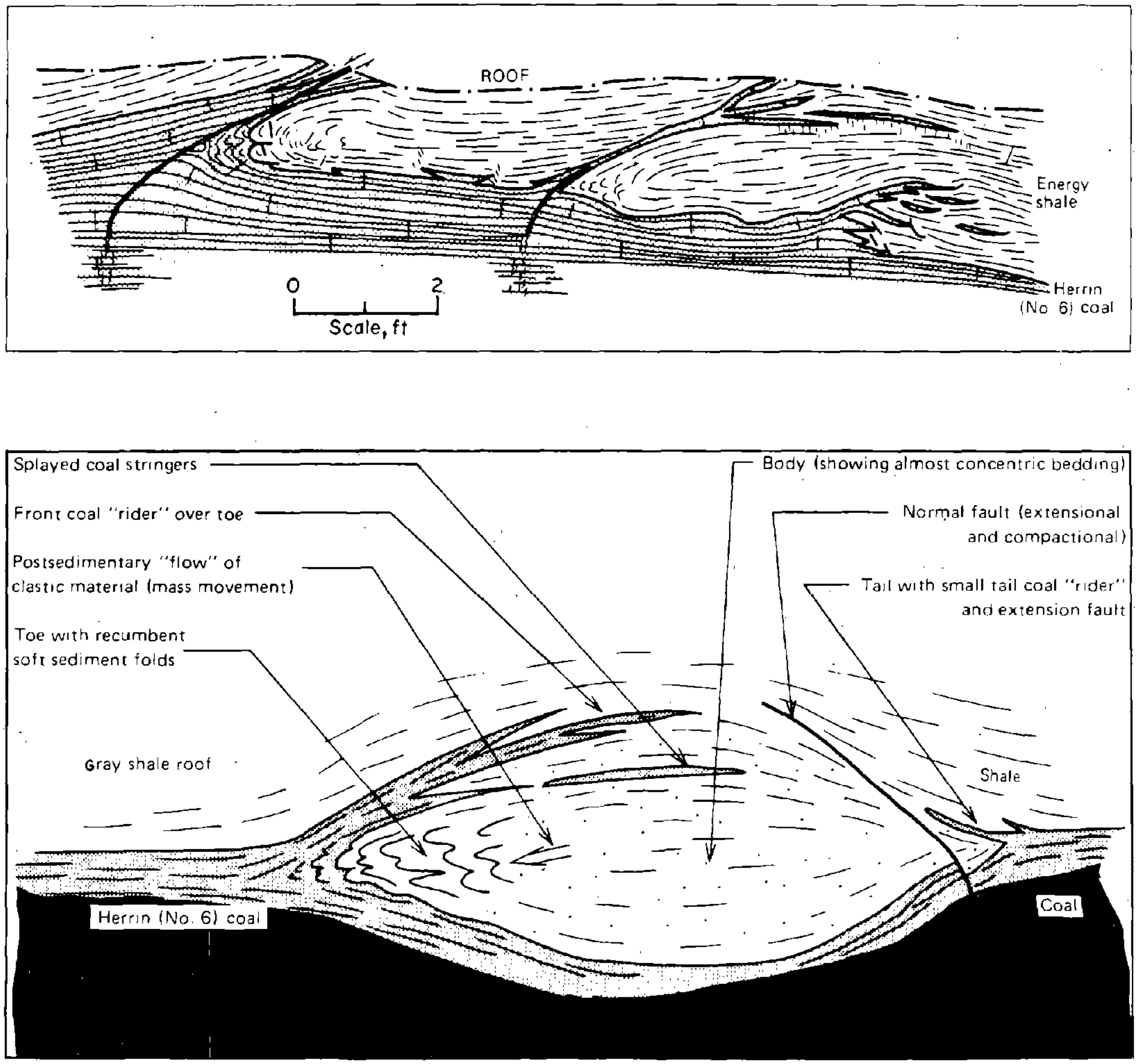

FIGURE 8. - Roof rolls in the Herrin Coalbed (19). Top: Illustration shows coal stringers that have been split off from coalbed, folded toes of the rolls, and low-angle normal faults that steepen downward and dissipate into the coal. Bottom: Typical soft-sediment protrusion of sandy material into surrounding coal, shales, and siltstones.

Roof control plans and entry projections should be flexible enough to provide wide variability, because local geologic conditions that affect roof stability can only be projected for short distances with any precision.

REVIEW OF CONTRACT RESEARCH ON THE PHYSICAL PROPERTIES OF COAL MINE ROOF ROCK

FAILURE OF ROOFS IN COAL MINES, CONTRACT H0232057 (2)

This investigation was conducted over a period of 4 yr and chiefly involved three mines in the Herrin (No. 6) and Harrisburg (No. 5) Coalbeds in southern Illinois. The contract report, however, includes some findings of an earlier study of the deterioration of shales in coal mine roof (3). The objective of this investigation was to determine the effects of exposure to the humid mine air on the coal mine roof. The investigation also included underground studies of the geometry and location of roof falls, long-range continuous monitoring of mine air humidity, and measurement of roof deflection. Laboratory work was extensive and consisted of measuring the moisture penetration and absorption of roof shale and the resulting strain, temperature effects, and physical properties of roof rock.

Significant Findings

Field Studies

Monitoring at two operating mines showed that as air is taken into a mine it undergoes a rapid tempering; that is, the fluctuations in temperature and humidity are reduced by interaction with the underground environment. The distance inby at which the air becomes tempered and stable to nearly constant humidity and temperature is chiefly a function of the ventilation fan capacity for air flow, although the differential between surface and underground environments is also a factor.

Before surface air equalizes to underground conditions, there is an interchange of moisture between the air and mine rock. During humid summer seasons, the surface air is cooled, and moisture condenses on mine rock surfaces. In winter, the air is drier and absorbs moisture in the mine. The monitoring studies showed that when humidity levels changed, the moisture interaction with the mine rock was most rapid during the first 6 days after the change, and neither temperature nor barometric pressure had any significant effect on the moisture absorption capacity of shale roof.

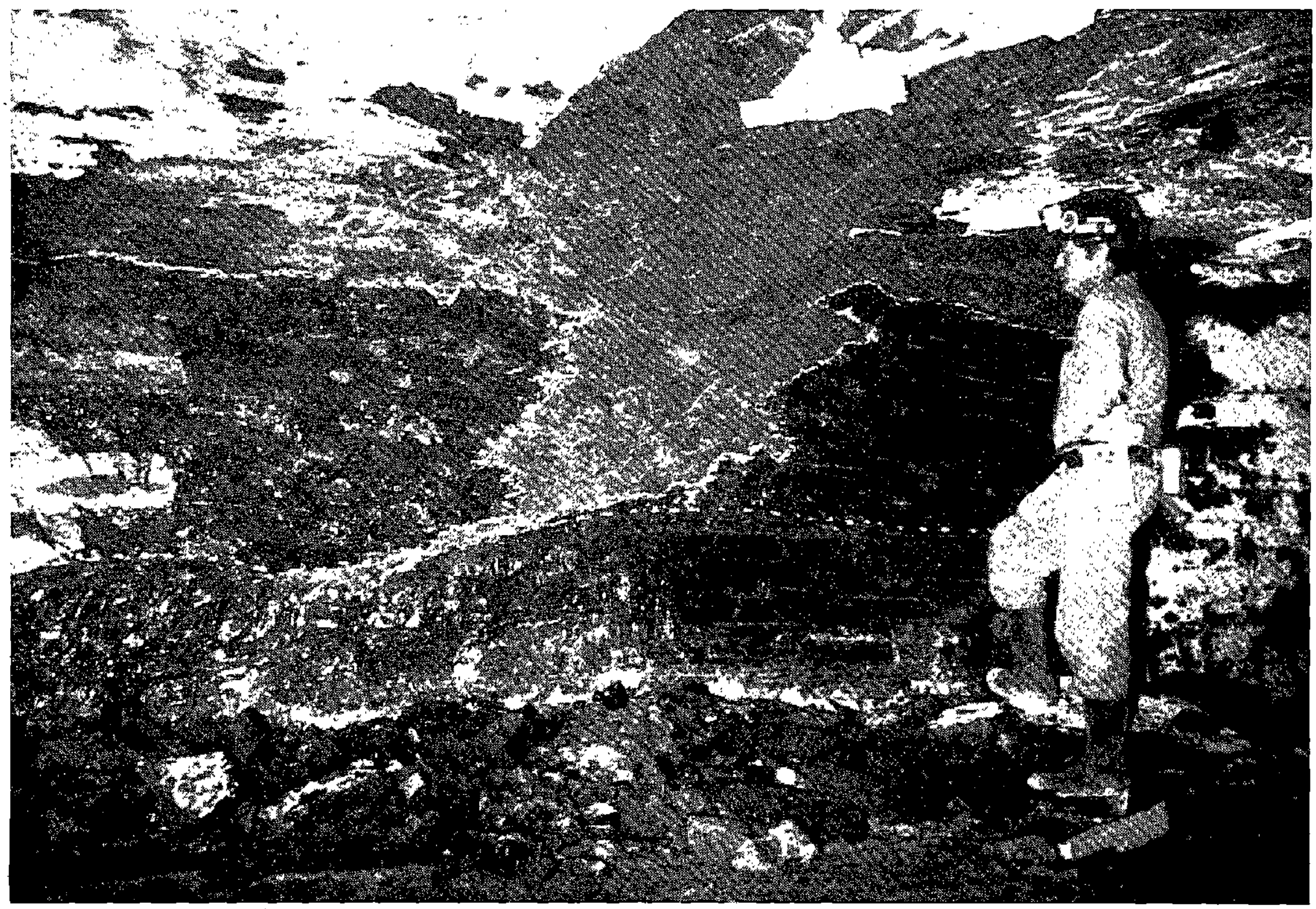

FIGURE 9. - Claystone dike or clay vein transecting coalbed and shale roof.

While roof shale will absorb or release water depending on the moisture level in the air, the net effect on mine roof was a more or less continuous downward deflection throughout all seasons despite short-term fluctuations in moisture, but some upward cycling of roof was observed. Measurements indicated that roof sag generally was greater in the spring and summer than in the fall and winter because of greater humidity. Also, the more constant the humidity level was on a seasonal basis, the greater stability was in terms of roof sag.

This study produced some indirect evidence that pointed to moisture penetration through roof-bolt holes as the cause of high swelling pressures in the shale, which resulted in the loss of roof-bolt anchorage and failure of roof.

Laboratory Studies

None of the numerous physical tests on mine roof shale samples proved satisfactory for quantitative evaluation of the shale for roof stability, although all tests demonstrated a reduction in shale strength with increased moisture. Slaking tests were inconclusive. No individual physical property or diagnostic test of shale roof rock yielded reliable estimates of roof behavior, as shown by comparison of these estimates with the field monitoring data. However, laboratory studies did reveal that water penetration of roof shale is 50 pct greater along bedding than it is perpendicular to bedding and that penetration is rapid up to 1/4 in deep, then greatly decreases. Moisture absorption in shale samples resulted in swelling pressures of up to 4,200 psi, according to calculations based on laboratory data.

Comment

This study described the tempering of humid intake air, the interaction of the air with shale roof, and the resulting roof sag. The roof sag was more or less continuous but greater in the spring and summer than in fall and winter because of increased humidity during spring and summer. Laboratory tests confirmed the reduction in strength of roof shale with increased moisture. This evidence suggests that roof support problems in mines with moisture-sensitive roof rock such as clay shale and claystone might be reduced by holding humidity levels to a minimum, especially during spring and summer. This could be accomplished by diverting intake air through tempering entries.

No reliable quantitative tests for moisture sensitivity of roof rock were developed. Simple qualitative exposure or immersion tests probably remain the most practical method for assessing the slaking potential of roof shales.

EFFECTS OF TEMPERATURE AND HUMIDITY VARIATIONS ON STABILITY OF COAL MINE ROOF ROCKS, CONTRACT H0122111 (16)

The objectives of this contract were similar to those of the preceding one (contact H0232057): to determine the response of shale roof to variations in temperature and relative humidity, to develop a reliable moisture sensitivity test for roof rock samples, and to apply the findings to mine design. The investigation was conducted at four mines in the Warrior coalfield of central Alabama operating in the Mary Lee, America, and Pratt Coalbeds. Roof rocks consisted principally of carbonaceous clay shales with some argillaceous sandstones. The underground studies consisted of periodic roof-strain measurements made with a mechanical device and continuous recording of temperature and humidity levels underground and on the surface. The laboratory studies consisted of strain measurements under controlled humidity and temperature on samples of roof rock using a wire-resistance strain-gauge technique. The physical and mineralogical properties of rock samples were determined.

Significant Findings

Field Studies

Measurements of mine air humidity levels and roof strain parallel to bedding yielded widely scattered data and poor statistical correlation. Roof-strain values were much lower than those developed in roof rock samples tested in laboratory environmental control chambers. The average measured roof strain underground was only 371 μin/in, or 16 pct of the average strain developed in the laboratory under similar humidity and temperature conditions, and probably was low due to the in situ confinement.

Moisture balance calculations showed that the mines tested absorb moisture during the summer and expel it during winter. This indicates that air tempering is needed mostly during summer months when moisture levels in the atmosphere are highest. Daily temperature variations underground ranged from 2° at 11° F at distances greater than 1,000 ft inby the portal and should directly cause only insignificant amounts of roof strain. Evidence of roof spalling was abundant in air-intake entries but was virtually undetectable in returns.

Laboratory Studies

The wire-resistance strain-gauge technique used in these studies provided accurate results for measurements of moisture-induced strain in roof rock samples performed in an environmental control chamber. The strain in samples of roof from Alabama coal mines ranged from 200 to 6,000 μin/in under simulated moisture and temperature conditions. The strain developed in these rock samples by normal temperature variations only was far less than that noted for humidity variations and should not contribute to roof problems. The roof rock samples reacted gradually to humidity changes over a period of 7 to 10 days before the developed strain stabilized. This slow adjustment to humidity changes seems to rule out daily humidity cycles as a factor contributing to roof problems.

The data on moisture-induced strain obtained in the laboratory did not compare well with the data obtained underground, although a high correlation coefficient was obtained for the laboratory data. Physical property tests on roof shale samples (slake durability, swelling index, and Shore hardness) did not correlate well with moisture sensitivity. No correlations were observed between the relative amounts of aluminum, silicon, iron, calcium, or magnesium; nor were the results of X-ray diffraction, mineralogical content, or petrographic description of any value in determining the sensitivity of roof shale to moisture. No montmorillonite or other interlayered clay minerals that swell on wetting were detected.

Comment

This study indicated that samples of roof rock, such as might be obtained from exploratory drill holes, could be tested in the laboratory for sensitivity to moisture using the wire-resistance strain-gauge technique in an environmental control chamber. While this method of testing would be impractical for most mining companies, selected samples could be tested in a commercial laboratory to confirm the results of far simpler exposure or immersion tests that could be performed at a field office. The poor correlation of laboratory and underground data, however, suggests that the utility of such laboratory tests is seriously limited.

As in the studies done under contract H0232057, evidence was presented that suggests the possibility of using air-conditioning chambers during the summer months to reduce humidity entering the mine and water sprays in winter to increase humidity. These opposing systems would serve to reduce the wide fluctuations in the moisture content of intake air.

CORRELATION OF MINE ROOF FAILURE WITH TIME ELAPSE BEFORE SUPPORT INSTALLATION, CONTRACT H0111413 (5)

The purpose of this investigation was to determine if a significant relationship exists between roof areas that are left unsupported for several hours or days and roof areas that eventually fail.

It is included in this review because geologic factors and their bearing on roof support also were studied.

The research was conducted at three underground mines operating in the Mary Lee Coalbed in the Warrior Basin of central Alabama. Depth of overburden ranged from 200 to 700 ft. Emphasis was on a systematic study of mining and support installation sequences, roof deflection, and roof rock properties. A finite-element model of a mine entry was constructed using assumed stress conditions and physical properties adapted from a laboratory test conducted on samples of roof rock.

Significant Findings

The results of time-lapse studies at three study sites were not consistent. At one site, there was no significant difference in roof stability between areas immediately supported by bolting and areas left unsupported for an extended period. At the two other sites, the areas of roof that eventually failed were left unsupported for two to three times the normal interval. Statistical analysis of roof fall data, however, showed a significant correlation at all three sites between roof fall area and the roof-bolt pattern, where the bolt pattern was defined as the bolt length times the bolt spacing squared. Other variables such as mining depth and entry geometry were of minor influence on roof stability.

Visual examination of the roof and roof falls at each study site revealed that almost all of the falls were closely associated with faults, joints, roof rolls, a contrast in roof lithology such as crossbedded sandstone lenses in predominantly shale roof, or other sedimentary structures.

Roof-deflection data, as measured by numerous rod-type single-position borehole extensometers installed in groups of three at depths of 5, 10, and 20 ft into the roof, was inconclusive because of suspected, but uncorrected, temperature effects. Extensometers were located at distances of 1 to 150 ft from the face and detected maximum movement of from 0.006 to 0.089 in, most of which occurred in the first foot or two of roof.

Comment

In this study, the geologic conditions at each underground site far overshadowed the effects of time lapse between excavation and permanent support. While roof failure frequently occurred where roof was left unsupported for extended periods, the correlation was not good; it seems more important to recognize changing geologic conditions as a key requisite for effective roof support. This would entail a considerable ability to assess roof structure and a flexibility in supplementary roof support methods. Nonetheless, the study presented some evidence that time lapse is a significant factor, particularly where mining is carried out under structurally weak roof.

CAUSE AND PREVENTION OF FAILURE OF FRESHLY EXPOSED SHALE AND SHALE MATERIALS IN MINE OPENINGS, CONTRACT G0111809 (4)

The objective of this study was to determine the mechanism by which coal mine roof rocks interact with mine atmospheres and weaken. The scope of the work was limited to some underground observations and chiefly laboratory tests on samples of shale roof rock to determine how the rock changed after exposure to controlled humidity levels. Samples for testing were collected from coal mines near Price, UT; western Washington; Weld County, CO; and Raton, NM. Roof conditions generally were bad at the sampling sites, although the cause of the bad roof was unknown. The laboratory tests included mineralogical determinations, Shore hardness, slake durability, fabric analysis, sonic velocity, and electron-beam microanalysis.

Significant Findings

Shore hardness decreased and specimen weight increased up to 1.7 pct after shale roof samples were exposed to

100-pct relative humidity. Constant weight was reached in 4 to 7 days. Any abrupt increase from a low to a high humidity (of nearly 100 pct) caused many specimens to break, although gradual increases avoided breakage. Shore hardness, considered by some to be a rough indication of rock competence, increased with silica content of shale and decreased with clay content. No evidence of sample swelling was detected by X-ray diffraction. However, there was a lack of correlation between all the laboratory tests performed and the observed behavior of large pieces of shale both within the mine and in the laboratory. Montmorillonites were seldom found in the roof samples studied, and quartz was the only nonclay mineral present in major amounts. Except for montmorillonite, the same minerals occurred in all samples of roof, but the relative amounts varied widely even in different portions of the same specimen.

Comment

This project characterized the difficulties and failures that have been common in attempts to perfect a reliable physical property test that alone shows a useful correlation with the weakening effects on roof rock exposed to humid mine atmosphere. The problem is complex because the textural and mineralogic attributes of roof shale are highly variable, while microscopic features such as small fractures, slickensides, laminations, and internal structures predominate as factors in overall strength and are difficult to distinguish even in laboratory specimens.

Finding a practical but quantitative and measurable parameter that is a diagnostic of roof shale stability in humid mine air remains a challenge.

CONTROL OF SHALE ROOF DETERIORATION WITH AIR TEMPERING, CONTRACT J0188028 (6)

The objective of this contract was to evaluate the effectiveness and feasibility of using air tempering (AT) entries in coal mines to reduce or stabilize humidity levels in mine air and thereby control roof slaking.

The long-term effects of mine air humidity on shale roof have not been fully assessed, although roof disintegration is severe in many intake entries and near shaft bottoms, and laboratory tests have confirmed that moisture invariably weakens samples of shale roof. The use of multiple entries or rooms as air-conditioning chambers to control roof disintegration has been attempted with varying degrees of success, but documentation has been poor.

Under this contract, all available literature relating to AT was compiled and an annotated bibliography was prepared. This was followed by long-term on-site monitoring of a mine where the effectiveness of air-conditioning chambers was fully documented. The results of this investigation were used to develop design criteria for the use of AT chambers. Also, a moisture sensitivity test was developed for use on exploratory drill-core samples of roof shale.

The mine air and roof conditions in the AT and inby entries of a mine near Wheeling, WV, were monitored for 12 months. The air temperature, air humidity, barometric pressure, and flow rates were measured almost continuously, while roof disintegration in the AT entries was assessed periodically through convergence measurements, the collection of fallen material, Schmidt Hammer tests, photographic logging, changes in roof height, and detailed mapping.

Significant Findings

Field Studies

The monitoring of mine air clearly showed seasonal effects. During winter, temperatures are low and consequently absolute humidity is low, so the roof shale is deprived of moisture. During the summer, absolute humidity and temperature rise, so the roof shale absorbs moisture. Thus, shale roof is subject to extreme wet and dry cycles which are greater near the shaft than farther inby and beyond the AT entries. Temperature equilibrium was largely complete within 5 min residence time, while humidity required about 30 min to stabilize. Velocity within the AT entries should be less than 300 ft/min. In midsummer, air temperature drops radically as air passes into the AT entries, condensation occurs on the mine roof and walls, and the atmospheric moisture content drops rapidly until about 20 min air residence time. In midwinter, colder temperatures reduce the absolute humidity of intake air to low levels; however, there is little exchange of moisture between rock and air, due to dryness of the rock, until after warming takes place and some moisture is re-absorbed by the air. Air tempering thus has the effect of evening out both temperature and humidity levels before the air is diverted into the main entries.

During midsummer, the AT entries were foggy and roof surfaces were wet. Deterioration of the roof was marked by almost continuous falls of small pieces of roof rock. Deterioration was most severe near the inlet, where the air was warm, and near clay veins. Near the outlet to the main entries, the air was cooler and clearer, the roof was dry, and the roof fragments fell much less frequently. In winter, the AT entries were cool and dry, and roof disintegration stopped. Little deterioration of the main entries occurred throughout the year. The zones and times of maximum roof sag correlated with the changing positions of mine air equilibrium zones. Some initial disintegration of roof was attributed to remnant fugitive moisture from the developmental mining cycle. Roof consisting of unlaminated, slickensided claystone disintegrated rapidly on exposure, while gray and black laminated shale showed no slaking tendency.

Laboratory Studies

Samples of roof rock were subjected to tests for static slaking, natural moisture content, null-point humidity (at which the rock will neither take up nor give up moisture), and shale expansion at various humidity levels. These tests were conducted to determine if the results would be indicative of roof shale deterioration upon exposure to variable humidity levels. Only shale expansion gave a reliable indication of potential disintegration, but the method used is somewhat complicated and costly for routine use.

Cost Benefit

The cost effectiveness of using AT entries was estimated on the basis of several assumptions because reliable values for the various factors involved were unavailable. The AT entries used at the mine studied were shown to be cost effective, due to a reduced need for maintenance in the main entries. Although AT entries have a high initial cost and deteriorate with time (accounting for the term "sacrificial entries"), the cost is more than offset by lower operating costs. In addition, the hazard of roof spalling in the main entries is reduced.

Comment

This investigation constitutes the first well-documented assessment of AT entries and, as such, may not be representative of other mining districts where different climates, conditions, and roof rock prevail. However, for the upper Ohio River Valley, this study demonstrated that wide ranges in humidity levels can be controlled. While the AT entries were subject to severe roof disintegration, the roof of the main entries was not subject to wide fluctuations in humidity and remained stable, requiring little if any maintenance. The study indicated that the moisture sensitivity of samples of roof rock can be estimated by using a shale expansion test performed on exploratory drill-core samples prior to mining. This, along with some of the design criteria developed for AT entries, should provide mine planning engineers with better guidelines for controlling mine air humidity than were previously available. It was concluded that the life of AT entries is impossible to predict but can be extended by the installation of wire mesh on the roof or some degree of maintenance such as clean-up, re-posting, and/or re-bolting.

CONCLUSIONS REGARDING GEOLOGIC STRUCTURE AND LITHOLOGIC CHARACTER OF MINE ROOF

In the studies conducted under three contracts H0133018, H0230028, and H0242017, in which the geologic character of mine roof and its relation to roof stability were assessed, two structures were found to predominate over all other features in the areas studied as factors that directly contribute to a large portion of roof failure. These are roof rolls and slickensides.

ROOF ROLLS

This term includes any abrupt downward protrusion of sandstone or shale roof rock into the top of the coalbed or into the shale and coal rash immediately above the coalbed. A common form of roof roll is shown in figures 1 and 4. Roof rolls may consist of individual troughlike sandstone- or shale-filled channels and scours or the convex undulations at the base of a thick sandstone member of roof rock. Slickensides invariably occur around the bases and flanks of the rolls, which along with the rolls interrupt the continuity and beam structure of the roof strata. In addition to the slickensides, the effects of differential compaction marginal to roof rolls include fracturing, small-scale bending and folding, and minor faulting. Rolls consisting of permeable sandstone commonly contain ground water which is released into the mine entries, thereby contributing to problems of mine haulage and roof deterioration. Roof falls are most likely to occur adjacent to the rolls and beneath the base, where slickensides are most prevalent. The hazardous nature of paleochannels (roof rolls) has been described by Moebs and Ellenberger (22).

Rolls can be identified and mapped underground and sometimes projected from 400 to 2,000 ft into unmined coal if the linear trend is very pronounced, although many rolls are discontinuous.

Only a general indication or probability of roll occurrence can be deduced from drill-core data. The presence in core of conglomerate, irregular coal streaks, and distorted bedding might indicate the proximity of a roll. Variations in the interval between the coalbed and the base of a thick sandstone suggest an undulating contact that might be troublesome if it is within 15 ft of the roof.

SLICKENSIDES

Slickensides are particularly common around the margins of roof rolls but occur throughout most fine-grained rocks such as claystones (fig. 3), also known as clod rock or seat earth, and clay shales. Slickensides constitute one of the most common causes of roof falls of all sizes because they interrupt the continuity of roof strata, forming wedge-shaped segments of rock that are difficult to support. They can be identified readily in drill core, but any prediction as to their distribution and density is best based on the distribution of their host rock, because a slickenside count from drill core represents an exceedingly small and probably unreliable sampling.

The preceding relationships were established through the contract studies conducted in eastern Kentucky, southern West Virginia, and southern Illinois. Similar relationships were observed in many mines in the Pittsburgh Coalbed of southwestern Pennsylvania, indicating the widespread occurrence of these types of roof problems. Roof rolls at one mine in southwestern Pennsylvania are described in detail in a Bureau report by Moebs (21), while a study of slickensides at a mine in the northern West Virginia panhandle is discussed by Ellenberger in another report (11).

Supplementary roof support for rolls and slickensides customarily consists of bolting, using blocks and metal straps, with an occasional post and crossbar or rail. Angle bolting may offer some advantage but rarely is used.

In addition to roof rolls and slickensides, three features of lesser importance in roof instability emerged from these contract studies: interlaminated shale-sandstone-coal, joints, and clay dikes (or clay veins). These three features are discussed below.

INTERLAMINATED SHALE-SANDSTONE-COAL

The combination of poorly bonded, thinly bedded, and often rippled strata with mica-rich layers is nearly always difficult to support and prone to separate and fail progressively layer by layer. According to Moebs (22-23), this rock unit can best be described as a crevasse splay, and it occurs most commonly in the lower part of a sandstone. It is known to miners as trashy or rashy sandstone, or stackrock if it is predominately sandstone. Examples of shale-sandstone-coal are shown in figures 4 and 5. Interlaminated strata can be readily identified in drill core. The lateral distribution of this type of roof is erratic, but can be approximately outlined; and the thickness can be represented by an isopach map. Experience indicated that in either laminated or soft roof, resin bolting is more effective than mechanical bolting.

JOINTS

Care must be exercised in distinguishing between a slickenside--a usually curving, polished, and striated surface--and a joint--a plane surface (always vertical, or nearly so, in the bituminous coal region) that occurs in parallel sets of widely varying density. Only one contractor found jointing to be of even doubtful significance to roof conditions, and then only under shallow cover, essentially in the zone of weathering under stream valleys and near the outcrop line.

In areas of the northern Appalachian region where overburden is less than 600 ft, over 90 pct of severe roof instability, often called "snap top," occurs beneath narrow steep-walled valleys, according to a preliminary Bureau survey of operating mines. Underground evidence strongly indicates lateral stresses due to topographic effects as the cause, rather than jointing, which was first suspected. Roof instability caused by high lateral compressive stresses is usually characterized by the shears or "cutters" that develop at the intersection of roof and rib (fig. 10). Shears can sometimes be controlled by angle bolting. Under severe stress conditions, roof bolting alone will seldom support the roof, and posts with crossbar or cribbing must be used, or reorientation of workings may help.

Even though jointing was not considered a major cause of roof failure in the mines studied with respect to the geologic character of mine roof, the authors recognize that joints are sometimes significant contributing factors to roof instability. For example, the final report for contract H0111413 repeatedly points out the relationship of joints to roof falls that were studied in that investigation. Stateham (31) encountered a joint-controlled area of roof instability in a study in Colorado. Scheibner (28) mentions joints as a major contributor to roof falls in Utah. On the basis of very limited information, joint-related roof falls appear to be more prevalent in the Western United States than the Eastern United States.

CLAY DIKES

Clay dikes, or clay veins, were identified by only one contractor as constituting an occasional roof support problem in the Illinois Basin. Available data for other areas were incomplete. While clay dikes occur in many coalbeds over a wide area of the northern Appalacian coal

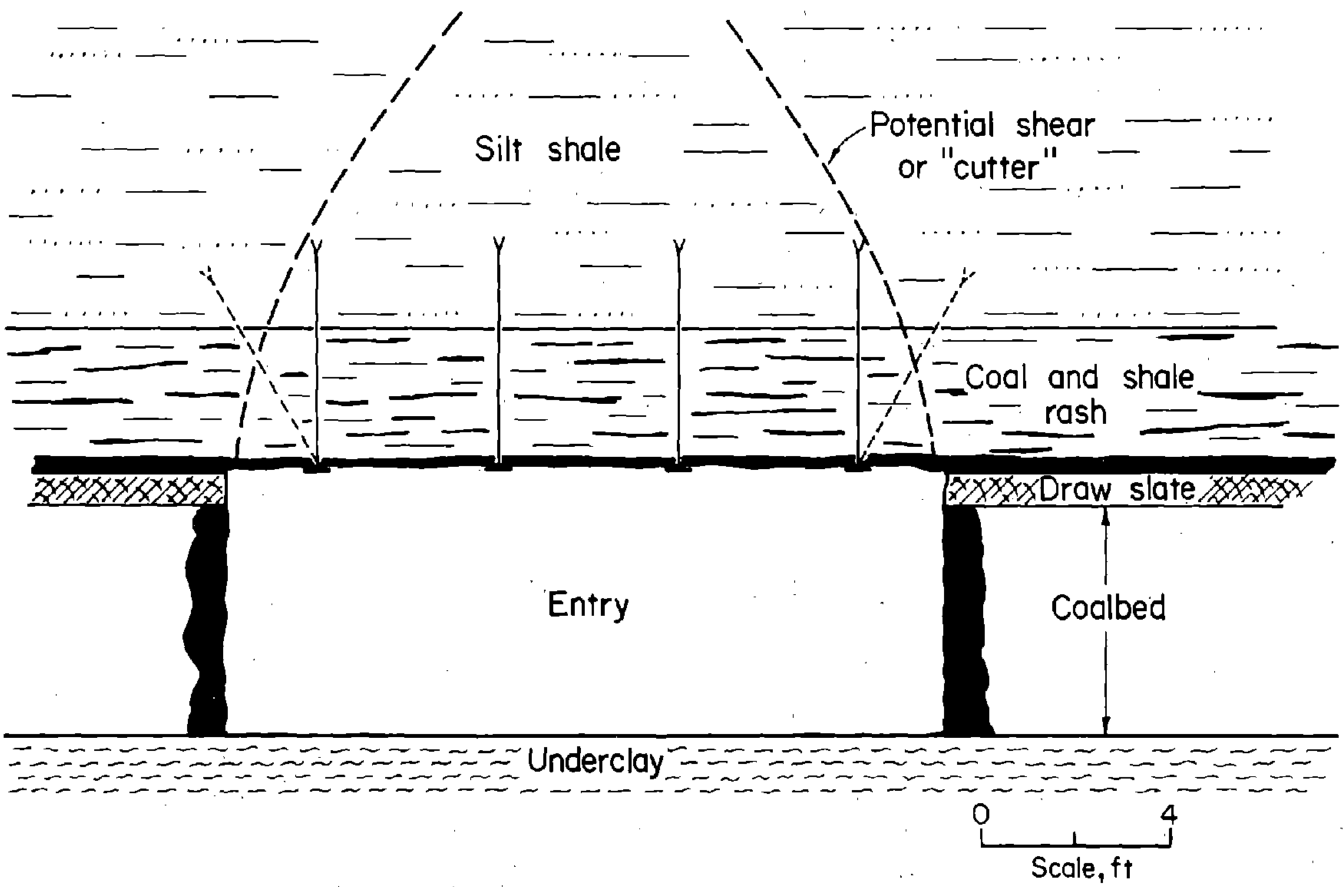

FIGURE 10. - Shear- or "cutter"-type roof failure developing along rib line.

region, they are particularly large and abundant, and a serious problem, in the Pittsburgh Coalbed in the upper Ohio River Valley. Here, as in the Herrin Coalbed in Illinois, clay dikes are most common where the immediate roof consists of a few feet of claystone or clay shale overlain by limestone. Clay dikes also occur in the West, where they are more commonly called spars or rock spars. Dunrud (10) mentions their presence in United States Steel Corp.'s Somerset Mine and states that they caused the closure of another mine (the Cameo Mine).

Clay dike widths range from a few inches to over 12 ft. The narrow dikes resemble clay-filled faults or joints, while the wide ones are broad and trough-like (figs. 2 and 9). Clay dikes are highly erratic in lateral extent but often exhibit a dendritic or desiccation pattern.

Clay dikes are virtually unpredictable by core drilling alone, although their occurrence might be conjectured based upon existence of the proper host rock, a soft claystone overlain by limestone or calcareous shale. Otherwise, projections based on underground mapping offer the best prospects for predictions. For example, important intersections and entries can be located so as to avoid the projections of significant clay dike trends.

The customary roof support consists of supplementary bolting using blocks, planks, or metal straps.

CORE MANUAL AND HAZARD MAP

The potential value of contract J0188115, which provided for publication of a guidebook for drill-core identification and classification, is self-evident and has been discussed. The degree to which the book is used will be a large factor in the success of future premining investigations that are based on descriptive drill-core data.

Similarly, the potential value of contract J0177038 rests with the application of the hazard zone base map concept and constant revision of the resulting maps as new information emerges from geologic studies or underground development. While the original base maps can be prepared through sophisticated computer analysis and plotting of drill-hole data, follow-up manual modifications in specific areas are essential to attain the maximum precision, and geologic judgments of the highest order are required.

The concept of a hazard potential map is not altogether new. One of the first examples devised was illustrated in Bureau of Mines Technical Progress Report 70 in 1973 (24). However, because of the subtle geologic complexities involved, it has not been widely adopted.

CONCLUSIONS REGARDING PHYSICAL PROPERTIES OF COAL MINE ROOF ROCK

ROOF DISINTEGRATION AND HUMIDITY

Of the five contract studies relating to the physical properties of roof rock, four attempted to resolve the problem of roof disintegration after exposure to humid mine air. Three of the studies (contracts H0232057, H0122111, and G0111809) together showed the following:

1. The weakening effects of moisture on shale roof were confirmed.

2. Both humidity and roof sag are greater in the spring and summer than in the fall and winter, but sag is more or less continuous throughout the year. (However, these findings are in contrast with the results of Bureau measurements which show virtually no sag in test areas for up to 2 yr.)

3. The more constant the humidity seasonally, the less the sag.

4. Temperature changes are insignificant in roof stability.

5. Only seasonal and not daily humidity variations have a significant effect on roof stability.

6. The moisture sensitivity of rock can be detected in the laboratory by measuring developed strain or changes in Shore hardness. However, a simple and reliable test for use on drill-core samples to predict the weakening effect of high humidity was not developed, largely because macroscopic features predominate over the effects of moisture. When used together, however, the laboratory tests and macroscopic features can be useful indicators of rock stability.

These findings support the conclusion reached in other reports (30-31) that humidity influences roof fall occurence rates. However, the severity, size, and distribution of roof fall occurrences remain undetermined, as does a method for reducing them.

A fourth study (contract J0188228) was directed at evaluating one of the few, yet controversial, methods for controlling humidity in a mine, the use of air tempering chambers. Few options are open to the operator for limiting humidity in mine air. One method that has been attempted in past years, but was poorly documented, is to use so-called tempering, sacrificial, or air-conditioning chambers in which air is passed through several long parallel entries at low velocity to increase residence time. In the summer, moisture is condensed and absorbed on rock surfaces in these chambers, and therefore less moisture reaches the inby workings. During fall and winter, dry incoming air recovers some moisture. Thus, the range in humidity is narrowed. The roof over these entries may disintegrate severely after a few years of use, as is common near the bottom of air-intake shafts.

Water sprays have also been used during the winter to maintain a moderate level of humidity in the otherwise dry air, thus preventing wide fluctuations from season to season; however, water handling and ice formation can be troublesome.

Sealants, to exclude air from roof shale, are used widely in entries near shafts and portals, but are costly and leave inby entries unprotected.

Moisture effects are subtle and difficult to assess, but it was concluded from monitoring at the Valley Camp Mine near Wheeling, WV, that air tempering entries are effective in controlling humidity and roof deterioration.

TIME LAPSE BEFORE ROOF SUPPORT INSTALLATION

The studies conducted under contract H0111413 indicated that while the time lapse between roof exposure and permanent support may be a factor in long-term roof stability, particularly where roof conditions are bad, the relation is difficult to establish. This is because the geologic character of the roof strata is a much greater and highly variable factor that probably contributes to the time-lapse relationship. A fuller assessment of the influence of roof geology on roof movement will be required before the effects of a time lapse prior to support can be reliably determined (26-27, 31).

In similar studies conducted by the Bureau in Colorado (28, 30, 32) it was concluded that once permanent support is achieved, the amount of time the roof was left does not appear to affect long-term roof stability in the mine investigated. These studies were conducted mainly in relatively strong roof rock. Roof sag was monitored in a mine section where roof bolting was delayed for up to 88 h after exposure. The rate of sag was high immediately after mining and before bolting, but fell to a low value and stabilized after bolts were installed. Also, roof fall occurrence was compared to time lapse, but no positive correlation was found. The roof in the mine studied was shale to sandy shale overlain by sandstone and was intensely slickensided (31). A total of five study areas were instrumented. One area was influenced by jointing. Another area was influenced by a roof roll and also by the swelling effects of montmorillonite when wet.

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INT.-BU.OF MINES,PGH.,PA. 27485