

CONTRIBUTIONS TO ECONOMIC GEOLOGY IN UTAH — 1986

By Mark D. Bunnell and Theodore W. Taylor

UTAH GEOLOGICAL AND MINERAL SURVEY

a division of

UTAH DEPARTMENT OF NATURAL RESOURCES

SPECIAL STUDIES 69

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INTRODUCTION

By Alex C. Keith

The support of graduate level geologic investigations within the State of Utah is an objective of the individual programs within the Utah Geological and Mineral Survey (UGMS). This support is done on a contract basis and includes money and various forms of equipment and tools. Both of the authors in this Special Studies publication were supported by the UGMS through such programs. Mark Bunnell was contracted through the coal geology program under the supervision of Archie Smith. Theodore Taylor was contracted through the metals program under the supervision of Hellmut Doelling.

Support for these students is initially based on a \$1,500 grant and the publication of their final report. Other assistance is offered to the students in the form of advice, field checking their work, and air photos and base maps. The student has completed his obligation to the UGMS when a final acceptable product has been delivered and the work has been field checked by UGMS staff members and other invited scientists.

The theses are then edited by the contract supervisor, other UGMS personnel, and selected non-UGMS professionals. The outside review of M. Bunnell's thesis was done by Prof. V. J. Hucka of the University of Utah Mining Engineering Dept. and Rick Smith, Engineering Geologist, Utah Division of Oil, Gas, and Mining. The comments which they provided were valuable in creating the final published report.

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by Theodore W. Taylor

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ROOF GEOLOGY AND COAL SEAM CHARACTERISTICS OF THE NO. 3 MINE, HARDSCRABBLE CANYON, CARBON COUNTY, UTAH

By Mark D. Bunnell¹

ABSTRACT

The No. 3 mine in Hardscrabble Canyon, Carbon County, Utah is an underground coal mine located in the Sub-3 seam, the lowest coal bed of the Spring Canyon coal group in the Upper Cretaceous Blackhawk Formation. To gain a more complete understanding of the mine, a geologic analysis was conducted which included underground mapping of roof rocks, measurement of stratigraphic sections throughout the mine, petrographic analysis of the coal and roof and floor rocks, and projection of roof lithologies into future mining areas.

Lithology and stratification of beds immediately overlying the No. 3 mine vary greatly due to rapid lateral changes in three major sedimentary facies in the mine roof including a fluvial channel facies, an overbank facies, and a swamp facies. The fluvial channel facies includes fluvial channel-fill sandstone bodies exposed in the mine roof. The overbank facies contains thinly bedded sandstone, siltstone, and mudstone. The swamp facies contains deposits of coal and carbonaceous mudstone.

Unstable roof conditions in the mine are, in general, closely related to various depositional facies in the mine roof and include: 1) roof falls associated with channel-fill sandstone bodies, 2) falls associated with overbank sandstone deposits, 3) falls associated with overbank siltstone deposits, and 4) "cathedral-type" roof falls which appear to be unrelated to immediate roof rock type.

The Sub-3 seam is a high-volatile bituminous coal. Lithotype bands in the coal seam are laterally continuous, comprised primarily of clarain and durain bands. Microlithotype analyses of polished columns showed percentages of microlithotypes within lithotype bands, and maceral analysis of the coal indicated a high-volatile B bituminous rank with a high percentage of vitrinite. Cleating in the Sub-3 seam is well developed.

Miscellaneous geologic features occur in the No. 3 mine that affect both mine roof and coal seam characteristics. These features include clastic dikes or "spars," rock splits or partings, coal seam rolls, coal bed methane and oil seeps.

Underground geologic mapping and analysis in coal mines provide mining companies with an understanding of

roof and coal seam conditions, as well as increasing their ability to predict geologic conditions in advance of mining. This understanding can help improve mine safety and production.

INTRODUCTION

During mining in the No. 3 mine in Hardscrabble Canyon, Carbon County, Utah, local unstable roof conditions have been encountered that have slowed mine production at times and, more importantly, have presented a safety hazard to mine personnel. Problems of roof control, coupled with other mining problems related to the geologic setting of the mine area, created the need for an in-mine geologic analysis of the mine roof as well as the mined coal seam.

This study was undertaken in an effort to establish and understand the geologic factors that affect the mine roof and to analyze the general characteristics of the coal bed. An attempt has also been made to project mine roof conditions into proposed future mining areas and to analyze the coal both megascopically and microscopically. With the present increased interest in efficient, safe, and cost-effective coal development, an understanding of the geologic parameters that affect coal and coal mining in the area is vital.

Coal being mined in the No. 3 mine is in the Sub-3 seam, the lowest coal bed of the Spring Canyon coal group in the Upper Cretaceous Blackhawk Formation. The Spring Canyon coal group forms the basal coal zone of the exposed Blackhawk Formation in the mine area and is underlain by a thick littoral marine sandstone unit. This massive sandstone is part of the basal Spring Canyon Sandstone Tongue of the Blackhawk Formation.

Regionally, the Sub-3 seam is reported to range in thickness from 20 cm (8 in) in western surface exposures (in sec. 8, T. 13 S., R. 9 E.) to 2.2 m (7.2 ft) in eastern exposures (in sec. 11, T. 13 S., R. 9 E.). The seam reaches a

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maximum thickness of slightly over 3 m (10 ft) in Hardscrabble Canyon and in Spring Canyon to the southwest (Clark, 1928). Within the projected mine area the seam, including 1 to 3 thin splits, is over 3 m (10 ft) thick but thins eastward and westward to less than 1.2 m (4 ft) (unpublished mine data). Rocks immediately overlying the Sub-3 seam vary from fine-grained sandstone to siltstone and shale. As early as 1932, it was reported that the Sub-3 seam exhibited a great variety of roof rocks (Tomlinson, 1932).

Field work for this study began in April of 1981 and was completed in October of 1981. Lab work began in October of 1981 and continued through May of 1982.

Location and Access

The main portal of the No. 3 mine is located in Hardscrabble Canyon, about 2 km (1.2 mi) northwest of Helper, Carbon County, Utah (figure 1). The mine area is located in sections 33, 34, and 35 of T. 12 S., R. 9 E. and in sections 2, 3, and 10 of T. 13 S., R. 9 E. The portal is easily accessible by means of a paved road which connects to U.S. Highway 6 about 1 km (0.6 mi) northwest of Helper.

Purpose of Investigation

In the past, the coal industry used geology primarily for exploration and delineation of coal tracts prior to mining, but in detailed mine planning and mine development, the science played a relatively minor role. With increased demands for efficient and cost-effective coal extraction, however, an understanding of the geology and depositional

environments of coal bodies is crucial. Exploratory drilling can provide coal companies with limited data on roof conditions and coal characteristics in a proposed mining area, but it cannot be used to effectively map local, yet relevant, lithologic or coal quality patterns only a few meters in lateral extent. These local irregularities commonly have the greatest influence on roof stability and local changes in coal quality and recoverability.

Production in the No. 3 mine has occasionally been hampered by such localized irregularities. Abrupt local variations in roof stability occur, as do localized coal bed discontinuities. In-mine geologic analyses of the roof and coal were undertaken to gain an understanding of why these local changes occur, where they occur, and what effect geologic parameters of the mine area have on roof and coal conditions.

The procedures of this study were: 1) to map roof lithology and to delineate and describe the depositional environments evidenced in rocks exposed in the mine roof; 2) to relate the roof geology to existing mine roof conditions and project expected roof conditions into proposed mine development areas; 3) to study the megascopic characteristics of the coal seam, including such characteristics as lithotype banding, methane content, cleat, rock interbeds, and coal seam discontinuities; and 4) to make a brief petrographic analysis of the coal and relate it to megascopic characteristics of the seam. This study should provide a significant addition to the existing geologic data base of the No. 3 mine, as well as provide insights into the geologic considerations of coal mine roof conditions and coal seam characteristics of the area.

Previous Work

Although several studies of the coal geology and stratigraphy of various Utah coal fields have been made, studies of individual coal mines or coal seams are few and commonly limited to one or two characteristics of a mine or seam. In the United States, most detailed studies of coal mine roof geology and coal seam characteristics have been conducted in eastern coal fields; and many of these have been successful in predicting roof and coal conditions in advance of mining.

Taff (1906) was one of the earliest workers in the Book Cliffs coal field, of which the Hardscrabble Canyon area is a part. His study consisted of a brief reconnaissance survey of the Book Cliffs coal field. In 1925, Spieker and Reeside named the coal-bearing Blackhawk Formation, with its designated type section by what was called the Blackhawk Mine near Hiawatha, Utah.

The first extensive work that included the Spring Canyon coal group was done by Clark (1928). He gave surface-exposure thicknesses for the Sub-3 seam and described lithology, stratigraphic relationships, and coal quality of the Spring Canyon coal group. Spieker (1931) correlated what is now called the Sub-3 seam with the Hiawatha seam of the Wasatch Plateau coal field. Young (1955, 1957, 1966, and 1976) delineated the stratigraphy, sedimentary facies, and

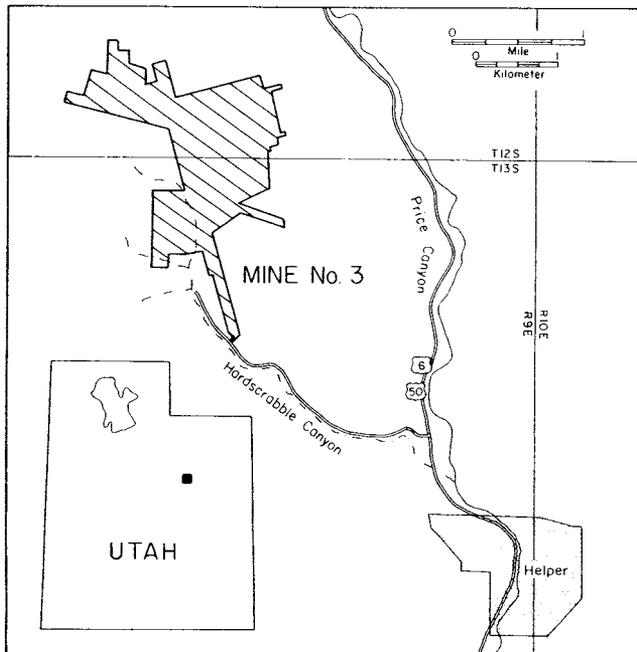


Figure 1. Location map of mine No. 3, Hardscrabble Canyon, Carbon County, Utah.

facies relationships of the Book Cliffs coal field. Doelling (1972), in a quadrangle approach to the coal fields of Utah, described the general characteristics of the Sub-3 seam in the Hardscrabble Canyon area as part of his description of coal in the Castlegate-Kyune quadrangle. Depositional models for the Blackhawk Formation in the Book Cliffs area of eastern Utah are discussed in a study by Balsley (1982), who also treated the effects of various depositional environments on coal deposits in the area. In recent studies by Blanchard (1981) and Mercier and others (1982), the Spring Canyon coal zone is correlated with the Hiawatha seam to the south.

Only limited studies of the No. 3 mine or the Sub-3 seam have been made. Tomlinson (1932) observed roof conditions in coal mines in the Sub-3 seam and noticed not only the great variety of roof rocks but a tendency for hazardous roof conditions to exist in the mines as well. McCulloch and others (1979) studied cleat orientations in the No. 3 mine and found that the butt cleat is roughly parallel to the axial trend of a nearby anticline. Doelling and others (1979) gave methane desorption data and proximate analyses for the Sub-3 seam from samples taken within the No. 3 mine area.

Other work includes studies of coal characteristics and mine roof geology in other area coal mines. Howard (1972) indicated some of the possible effects of channel-fill sandstone bodies on coal and mine roof conditions in the Book Cliffs coal field near Sunnyside, Utah. His observations were limited, however, to outcrop and drill hole information, and no actual in-mine observations were conducted. The first detailed in-mine analysis of effects of geologic conditions on coal mining in the east-central Utah area was conducted by Mercier and Lloyd (1981) in two coal mines in the Wasatch Plateau coal field, about 50 km (30 mi) south of the No. 3 mine. They found that mine roof lithologies had a profound effect on overall roof conditions and that many roof failures occurred at boundaries of channel-fill sandstone bodies with overbank/interchannel deposits. Numerous coal mining companies in east-central Utah have recently started programs of in-mine geologic analysis.

Numerous workers in coal fields of the eastern United States, including McCulloch and Duel (1973), Overbay and others (1973), Ferm and Melton (1975), Horne and others (1978), McCabe and Pascoe (1978), Krausse and others (1979), Jeran and Jansky (1983), and Moebs and Stateham (1984), have studied the effects of roof lithology and other geologic parameters on coal and coal mine conditions. Although these studies were conducted in other regions and the depositional settings may differ to varying degrees, the principles which were applied and the types of observations they made have been valuable to guide data accumulation and interpretation during the present study.

Present Study

The present study is a result of a continuing program of coal and coal mine analysis of Utah coal fields sponsored by the Utah Geological and Mineral Survey. Some of the data used in this study were supplied by the mine company,

including data from numerous drill holes and information from confidential mine studies.

Methods of Study

This study was conducted in four phases. Two phases involved in-mine analysis; two phases involved the gathering and interpretation of drill hole data and petrographic analysis of roof rocks and the coal seam.

The first phase involved detailed mapping of mine roof rocks and characteristics in all accessible areas of the coal mine. Mapping was done on a 1:1200 scale on existing maps supplied by the company. Lithologic boundaries exposed in the immediate mine roof, as well as other features such as roof falls and clastic dikes, were plotted on mine entries and crosscuts, and then projected across coal pillars. Paleocurrent orientations on exposed sedimentary structures were also measured and plotted.

The second phase involved measurement of 73 stratigraphic sections at selected locations within the mine. Sections were measured at approximately 30 to 35 m (100 - 155 ft) intervals (on each coal pillar) in three areas to determine the lateral continuity of various coal seam characteristics. Once lateral continuity of a characteristic was established, other sections were measured at more widely spaced locations throughout the remainder of the mine. Coal thickness, as well as thickness of lithotype bands within the seam, were measured and described in detail. During this phase, roof rock samples as well as channel and column samples of the coal were taken for petrographic analysis. Numerous mine gas samples were also obtained.

Phase 3 consisted of an analysis of 59 drill holes in the proposed mine area. Coal seam characteristics were studied along with immediate roof lithology. From information gathered during this phase, an isosand map of the proposed mining area was produced. Isopachous and interburden maps were also utilized in this phase to aid in the preparation of the isosand map.

Phase 4 consisted of preparation and analysis of roof rock thin sections and polished coal columns and pellets. Eight thin sections were prepared from various roof lithologies and analyzed petrographically for a general understanding of grain size and composition. Two polished coal columns were prepared, from which data regarding maceral content and vitrinite reflectance were obtained. Proximate and ultimate analyses were also run on two channel samples of the coal bed.

GENERAL GEOLOGY

The No. 3 mine is located in the northwest portion of the Colorado Plateau, in the northwestern end of the Book Cliffs of east-central Utah. Rocks in the mine area consist entirely of Upper Cretaceous sedimentary units that dip gently to the northeast.

Stratigraphy

Exposed rocks of the immediate mine area include part or all of four Upper Cretaceous formations. From the base

up, these include the Mancos Shale, Star Point Sandstone, Blackhawk Formation, and Price River Formation (figure 2). These units form cliffs and ledges separated by slopes with variations produced by differences in erosion rates. Sandstone commonly forms ledges and cliffs, while less resistant siltstone, shale, and coal beds form the intervening slopes.

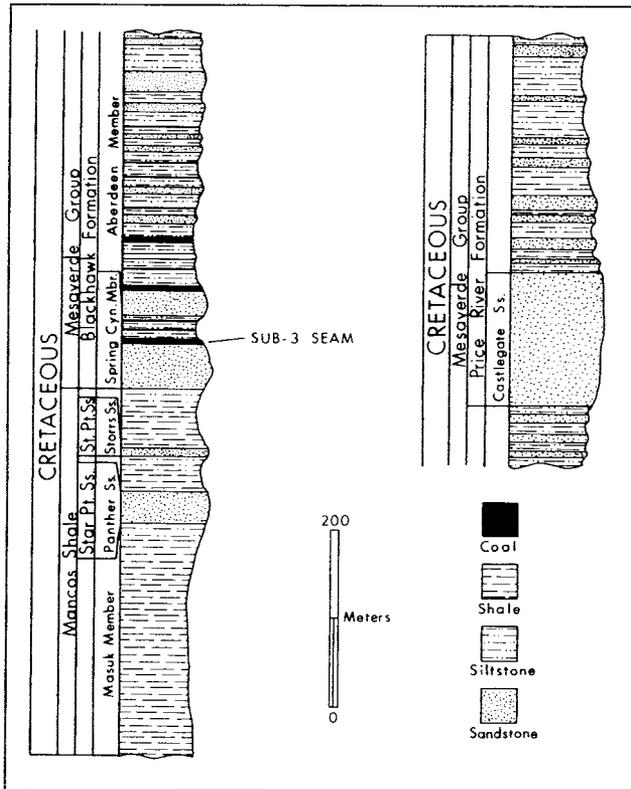


Figure 2. Generalized stratigraphic column of the No. 3 mine area showing the stratigraphic position of the Sub-3 seam.

Mancos Shale: The Mancos Shale forms a broad slope at the base of the Book Cliffs, as well as rounded hills and steep badland cliffs in the No. 3 mine area. It consists mainly of gray to bluish-gray to drab marine shale with local interbeds of sandstone and minor limestone. Only the uppermost portion of the Mancos Shale is exposed in the area, and it grades upward into, and interfingers westward with, two marine sandstone tongues of the Star Point Sandstone. Rocks at the contact between Mancos Shale and overlying tongues of the Star Point are reported to be early Campanian (Young, 1966).

About 300 m (1000 ft) of the upper Mancos Shale is exposed in the area and has been identified as uppermost Masuk Member by Young (1955 and 1966). A westward-thinning tongue of Mancos Shale overlies the lowermost tongue of the Star Point Sandstone. This represents only

one in a whole series of regional intertonguing clastic wedges that occur in the contact zone of the Mancos Shale with the Star Point Sandstone of the Mesaverde Group.

Star Point Sandstone: The Star Point Sandstone is the lowest formation in the Mesaverde Group in the No. 3 mine area. It is a prominent cliff former and consists of two eastward-pointing tongues of medial Campanian age. The basal sandstone tongue is the Panther Sandstone and the upper tongue is the Storrs Sandstone (Young, 1955). The Panther Sandstone is 30 to 40 m (100 - 130 ft) thick in the mine area, and the Storrs Sandstone tongue is about 5 to 10 m (17 - 30 ft) thick. About 40 m (130 ft) of Mancos Shale separates the two units.

The Panther Sandstone has been studied in detail by Howard (1966). It consists of siltstone at the base and grades upward into beds of massive, well-indurated, cross-bedded marine sandstone. The Storrs Sandstone consists of siltstone at the base and grades upward into beds of soft, friable sandstone. In the Helper, Utah area, the top of the Star Point Sandstone was placed at the top of the Storrs Tongue by Young (1955), who recommended lowering the formation boundary to exclude the overlying Spring Canyon Sandstone tongue, originally included in the formation by Spieker and Reeside (1925). Mercier and others (1982) recently proposed that the Panther and Storrs tongues of the Star Point Sandstone be included in the basal portion of the Blackhawk Formation because coal beds occur above each of these units in parts of the Wasatch Plateau.

Blackhawk Formation: The Blackhawk Formation includes the major coal-bearing rocks exposed in the western Book Cliffs and the eastern front of the Wasatch Plateau. In Spring Canyon, just south of the No. 3 mine, the Blackhawk Formation consists of about 300 m (1000 ft) of interbedded sandstone, shale, and coal (Young, 1955). Spieker and Reeside (1925) originally placed the lower boundary of the Blackhawk at the base of the lowest coal bed exposed in the Book Cliffs and the Wasatch Plateau, which is the base of the Sub-3 seam in the mine area. However, Young (1955), as previously mentioned, lowered the formation limit to the base of the Spring Canyon Sandstone tongue of Clark (1928). The upper boundary of the Blackhawk Formation is disconformable at the base of the Castlegate Sandstone. Blackhawk rocks overlie Star Point rocks but are still of medial Campanian age (Spieker, 1931).

Regionally, the time-transgressive base of the Blackhawk Formation consists of six prominent littoral marine sandstone tongues, as well as many lesser ones, all projecting eastward into the Mancos Shale where they lose their identity by grading into shale (Young, 1955). In the mine area, as mentioned previously, the basal sandstone tongue of the Blackhawk is the Spring Canyon Sandstone tongue. The Spring Canyon Sandstone tongue (about 50 m or 170 ft thick in the mine area) and 20 to 30 m (66 - 100 ft) of overlying coal-bearing shale and sandstone form the Spring Canyon Member of the Blackhawk Formation. The coals within this member are known as the Spring Canyon coal

group (Clark, 1928). The Sub-3 seam, in which the No. 3 mine is located, is the lowest of three major coal beds in the Spring Canyon coal group. Clark (1928) and Spieker (1931) originally correlated the Sub-3 seam to the Hiawatha seam, a major coal that directly overlies the Spring Canyon Sandstone tongue in the Wasatch Plateau to the south. Blanchard (1981) and Mercier and others (1982) also indicate that the two coals, or at least the two coal zones, may indeed be correlative.

Directly overlying the Spring Canyon member is the Aberdeen member, which includes the basal Aberdeen Sandstone and overlying coal-bearing sandstone and shale (Young, 1955). The lower sandstone tongue is about 26 m (90 ft) thick, and the overlying interbedded part of the member is 30 m (100 ft) thick in the Kenilworth area to the east. In the Hardscrabble Canyon area and to the west, however, the upper interbedded part of the member has no well-defined top and is included in the overlying 290 m (960 ft) of undifferentiated coal-bearing strata (Young, 1955).

As previously mentioned, the Sub-3 seam is immediately underlain by the Spring Canyon Sandstone tongue which makes an excellent floor rock for the No. 3 mine. Strata immediately overlying the Sub-3 seam consist of interbedded sandstone, shale, siltstone, and coal. Bedding relationships of these strata have a profound effect on No. 3 mine roof conditions.

Spieker and Reeside (1925) interpreted the general depositional setting of the Blackhawk Formation to be a broad coastal plain. Later studies by Young (1955, 1957, 1966, and 1976) and Howard (1966) indicated that the sandstone sheets or tongues represent barrier islands. Balsley (1982) suggested that most of the sheet sands were deposited by wave-dominated deltas, upon which the major coal beds developed.

Price River Formation: Spieker and Reeside (1925) separated the non-coal-bearing upper part of the Mesaverde Group above the Blackhawk Formation as the Price River Formation. In the vicinity of the No. 3 mine, the formation consists of the massive basal Castlegate Sandstone member, and overlying lenticular interbedded shale, siltstone, and sandstone. The Castlegate Sandstone Member forms a cliff about 150 m (490 ft) high, while overlying sandstone and shale units form ledges and slopes. The Price River Formation is approximately 400 m (1312 ft) thick near the No. 3 mine (Abbot and Liscomb, 1956) and is of Campanian and Maastrichtian age (Cobban and Reeside, 1952). The Price River Formation lies disconformably upon the Blackhawk beds in the mine area.

Structure

Rocks in the mine area, including the Sub-3 seam, generally dip 4 to 6 degrees to the northeast as part of the homoclinal structure of the northern Book Cliffs. Only a few faults are known in the general area, and these are 5 to 6 km (3 - 4 mi) west of the mine. They are relatively minor normal faults with maximum throws of about 7 m (23 ft).

No faults have been encountered in the No. 3 mine and none are apparent in the projected mine area. One gentle anticline occurs northeast of the canyon (Doelling, 1972). For the most part, strata in the immediate mine area indicate structural stability and no problems related to regional structure are expected to be encountered during future mine development.

Mining Operation

Mining in the No. 3 mine has utilized both room and pillar and longwall methods. Room and pillar extraction was the main method used until about 10 years ago when longwall mining was initiated. During the past several years, only continuous miners were being used for both development and production mining in room and pillar extraction. Due to coal market conditions, the mine is presently idle. In general, geologic conditions played a significant role in the efficiency and effectiveness of both the mining methods utilized in the mine.

The mine portal is located on the north side of Hardscrabble Canyon. Work was recently completed on two vertical shafts in Crandall Canyon to the north. One of these shafts will be used for transport of equipment and personnel into the mine. The mine workings generally underlie rather rugged topography which causes overburden depths to range abruptly from about 730 m (2400 ft) to less than 180 m (600 ft) beneath the steep-sided canyons and intervening ridges.

ROOF GEOLOGY

Lithology and stratification of beds immediately overlying the Sub-3 seam vary greatly in the No. 3 mine, largely because of abrupt lateral changes from one depositional setting to another. Because rocks of each of these depositional environments affect the mine roof somewhat differently, roof conditions may vary significantly over relatively short distances. Tomlinson (1932, p. 24) noted earlier that the greatest variety of roof conditions (at that time) above any Utah coals were those above the Sub-3 seam. He described the roof lithologies as varying from fine-grained sandstone to sandy-shale and shale, and observed that the roof is extremely treacherous. Abrupt variations in mine roof stability are still common above the Sub-3 seam, which occasionally creates safety hazards to mine personnel, and hamper mine production.

Numerous factors contribute to roof instability during coal mining. In the past, the most commonly studied factors included mining technique, mining sequence, mine orientation, rock strengths, entry width, pillar size, roof bolting technique, depth of mining, and roof hydrology. An understanding of these factors, indeed, is crucial to maintaining a stable mine roof, but only recently have detailed studies of the geologic characteristics of immediate mine roof strata been considered. Only during the past decade have coal mining companies in Utah initiated programs of detailed roof geology analysis. The present study is designed to fill this need in the No. 3 mine, where an understanding of ex-

isting roof lithology is important for maximum efficiency in mine roof control.

Lithology of the immediate mine roof (the 3 m or 10 ft interval above the coal seam) in the No. 3 mine varies from siltstone to very fine-grained sandstone with minor interbeds of mudstone, carbonaceous mudstone, and coal. Detailed mapping of exposed roof rocks differentiated major facies within a floodplain environment. These floodplain environments represent only a small part of the overall environment in which coal and other sediments of the Spring Canyon coal group accumulated.

Unstable roof conditions in the mine appear to be closely associated with either lenses of channel-fill sandstone or overbank sandstone deposits. It was possible, during roof mapping, to classify types of roof falls according to their occurrences in various depositional facies.

Sedimentary Facies of the Mine Roof

Three major genetic types of sedimentary deposits occur in the roof of the No. 3 mine. These include: 1) fluvial channel-fill deposits of sandstone, 2) overbank deposits of sandstone, siltstone, and minor mudstone, and 3) swamp deposits of coal and carbonaceous mudstone. Each has been mapped as a separate facies.

In general, a layer of thinly laminated overbank siltstone immediately overlies the Sub-3 seam throughout the mine workings. This siltstone, termed "caprock" by the miners, ranges up to more than 3 m (10 ft) thick in areas where no fluvial channel-fill or overbank sandstones occur. It is locally missing where the silt was scoured to peat level and the depression then filled with channel-fill sand. For the most part, however, even where the channel-fill and overbank sandstones occur, a thin layer of siltstone separates them from the underlying coal.

Fluvial Channel Facies: The fluvial channel facies is represented by channel-fill sandstone bodies that are exposed at numerous locations within the mine (figure 3). Many of these sandstone lenses are mappable for hundreds of meters in the mine roof until they pass into inaccessible or unmined areas. In general, the channel-fill bodies are massive, crossbedded, very fine-grained, moderately well-sorted sandstone. The sandstone has a calcareous cement and is moderately cemented and indurated.

Exposed bases of fluvial channel sandstone bodies range from about 9 to 60 m (30 - 200 ft) wide. These lenticular fills were observed to range from 1 m (3 ft) to over 4 m (15 ft) thick in overcasts and roof falls. Observations in canyon outcrops near the mine portal indicate that dimensions of the channel-fill sandstone lenses are relatively small in the mine area by comparison to channel-fill lenses observed in other coal mines of the Book Cliffs and Wasatch Plateau coal fields. For example, those observed by the author above the Castlegate "D" seam, about 150 m (500 ft) above the Sub-3 seam, reach a maximum width of approximately 600 m (2000 ft) and thickness of over 9 m (30 ft). Mercier and Lloyd (1981) indicated that migrating fluvial channels above the Hiawatha and Blind Canyon seams of

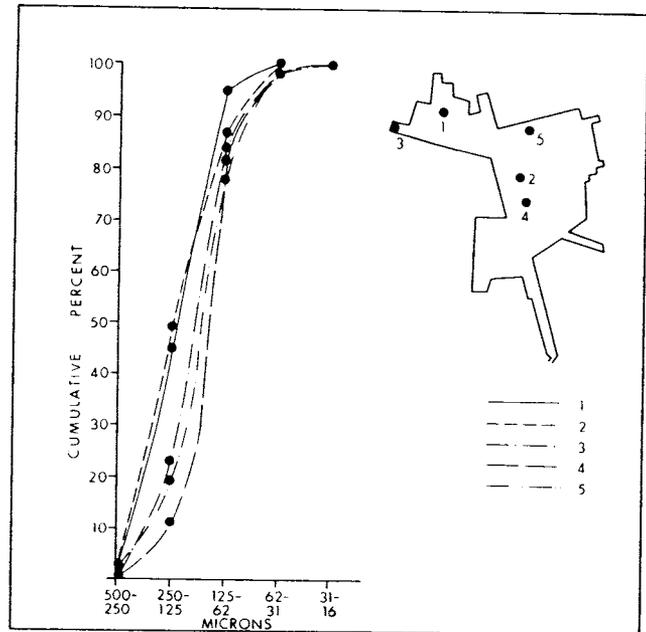


Figure 3. Cumulative frequency curves for five samples of channel-fill sandstone.

the Wasatch Plateau produced sandstone units with lateral dimensions up to several kilometers wide and up to 15 m (59 ft) thick. It is believed that the smaller size of fluvial channel fills in the No. 3 mine increases the lateral discontinuity of the roof geology, thus increasing the chances for lithology-related roof control problems.

Because only relatively small portions of the base of the fluvial sand bodies are exposed, it is difficult to determine the type of channel-fills represented. It is assumed, because of their relatively small size, that these lenses formed by avulsion or some other type of channel abandonment, rather than point bar accretion. Where observed in roof falls and overcasts, the channel sandstones commonly contain trough crossbed sets from 30 cm to 1 m (1 to 3 ft) thick, with local ripple laminae. Discontinuous shale laminae, up to 3 cm (1 in) thick, may occur and commonly form slickenside surfaces from differential compaction.

Basal surfaces of channel-fill sandstones in the mine roof are readily differentiable from other facies by their characteristic lateral discontinuity, convex-down shape, undulating basal surface, content of rip-up clasts of siltstone or coal, and local well-developed flute casts and tool marks. Trough crossbed sets are evident in the interior of the channel sandstone bodies but do not occur in either of the other facies.

Five thin sections of fluvial channel sandstone were made from samples taken at various localities. Thin section analyses indicate that grain sizes range from very fine- to fine-grained sand with calcite cement. Sand grains range from subangular to rounded, with subrounded grains dominating. General size distribution of grains in each of the samples is shown in table 1.

Table 1. Grain size distribution in fluvial channel samples

Sample No.	Micron Diameters					Number of Grains Counted
	500-250	250-125	125-62	62-31	31-16	
1	2	43	50	5	0	100
2	2	47	38	13	0	100
3	0	23	61	15	1	100
4	0	11	70	18	1	100
5	1	18	59	22	0	100

The 62 to 250 micron grain size dominates, with grains in the 62 to 31 micron size range also making up a substantial part in most samples. Cumulative frequency curves for the five samples indicate their general similarities (figure 3). All of the samples are well sorted and relatively clean, with some clay included in the calcite. It was not possible through in-mine observation of texture or through thin section analyses to find obvious differences between different channel-fill sandstone bodies. Each appears to have had the same source and to have been deposited in about the same energy regime.

Paleocurrent directions in the channel-fill bodies range dominantly northeastward-southeastward (plate 1). Flow directions were readily determined from trough crossbed sets, flute casts, and ripple marks. These flow directions generally appear to coincide with those obtained by other workers in the Wasatch Plateau and Book Cliffs coal fields. Mercier and Lloyd (1981) indicated a general northeasterly paleocurrent direction for sandstones mapped above the Hiawatha seam, above the Deer Creek Mine, south of the No. 3 mine. I have studied channel-fill bodies above the Castle-gate "D" seam that exhibit an east to southeast flow direction. In general a western source is indicated for many channel-fill sandstones of the Blackhawk Formation and those above the Sub-3 seam are no exception.

For the most part, channel-fill sandstone bodies make an excellent roof locally, especially when they are in direct contact with the coal seam and form the entire bolted roof. The paleochannel sandstones are generally massive and are not subject to delamination and deterioration. They are commonly only slightly jointed or not jointed at all. Nonetheless, numerous roof falls have occurred in the paleochannel bodies (plate 1), but these falls have occurred along thin mudstone laminae which were highly slickensided during differential compaction. In some cases, large blocks of the sandstone bodies have fallen, bringing down numerous rows of roof bolts.

The most hazardous roof conditions associated with sandstone bodies in the No. 3 mine occur where the sandstone is not in direct contact with the coal seam, but where the sandstone occurs in the mine roof from 20 cm to 2 m (8 in - 6.5 ft) above the seam. In this case, siltstone separates the coal and the paleochannel fill. In these areas, it appears that high stresses around the mine opening cause fractures to form within the brittle siltstone. These fractures generally increase in number and severity several days after mining, and large blocks and slabs of the siltstone begin to separate

from the overlying sandstone lens in sections between roof bolts. These concentric, parallel fractures seem to occur primarily in the differentially compacted zones beneath the channel-fill bodies.

During deposition, streams above the Sub-3 seam rarely had enough energy to scour through the layer of silt into the peat. It is common to find channel-fill bodies resting directly upon the coal seam, but seldom do any of them actually scour into the coal. Where scour is evident, generally only 5 cm to 1 m (2 in - 3 ft) of coal is missing, and even this erosion is very local. The peat, possibly due to its matted organic texture, was very resistant to channel scour. Major channel scours or "washouts" of portions of entire coal seams are known to occur in Wasatch Plateau and Book Cliffs coal mines, but because enough energy had to be present to scour the entire peat thickness, it is believed that such "washout" zones represent a much higher energy channel-fill deposit than is generally encountered in the No. 3 mine.

Another notable feature of these channel-fill sandstone bodies is that many of them are located above large coal seam "rolls" or undulations of the coal bed and the enclosing strata. A roll is a local miner's term for a localized downward or upward steepening in the dip of a coal seam. A typical roll in the No. 3 mine consists of a sudden steepening of the dip of the seam from 4 or 5 degrees to as much as 8 to 10 degrees within a lateral distance of 3 to 6 m (10 to 20 ft). Within 20 to 30 m (65 - 100 ft), the dip of the seam returns to its original dip and either stays that way or dips upward slightly for another 20 to 30 m (65 - 100 ft) (figure 4). Many of the larger channel-fill bodies in the No. 3 mine appear to follow roughly the same trends as the rolls which

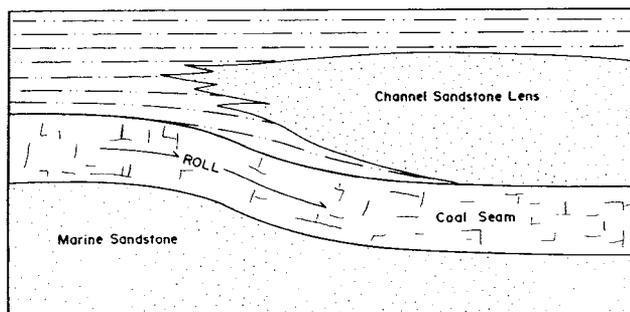


Figure 4. Generalized sketch of a coal seam roll.

leads to an, as yet, unanswered question. Are the paleochannels following paleotopographic features which we now observe as rolls, or are the rolls the result of differential compaction beneath the lenticular channel-fill sandstone bodies? A discussion of this question is included later in a section on coal seam rolls.

Ground water commonly occurs with channel-fill bodies, and, in fact, where dripping water was encountered in the mine, there was almost invariably a sandstone channel in the roof. Water from these sand bodies does not appear to be of major concern to mining in the No. 3 mine although, where it does occur, it may contribute to the weakenings of the immediate roof strata.

In general, channel-fill sandstone bodies can be recognized in the mine roof by the following characteristics:

1. They are composed of clean, calcareous, very fine- to fine-grained quartz sandstone.
2. They exhibit a convex-down basal surface with numerous small, rounded undulations, and in many instances flute casts are present.
3. Trough crossbed sets and lenticular bedding are common, with local ripple marks.
4. A zone of concentrically fractured siltstone occurs in the differentially compacted zone immediately beneath the sand body, creating unstable roof conditions.
5. An increase in water dripping from the roof is common, either directly from an exposed sandstone body or through the underlying fractured siltstone layer.
6. The coal seam may be locally scoured and/or compacted beneath the channel sandstone lense.
7. A coal seam roll may occur immediately beneath the channel-fill sandstone body.

Overbank Facies: Overbank deposits are common in the roof of the No. 3 mine and cover the greatest area of any exposed roof lithologies (plate 1). The overbank facies consists mainly of siltstone, sandstone, and local mudstone interbeds.

By far the most common lithology of the overbank facies is the siltstone "caprock" that immediately overlies the Sub-3 seam throughout virtually the entire No. 3 mine. The caprock is over 3 m (10 ft) thick in many areas of the mine and forms an excellent stable roof where no thin interbeds of overbank sandstone or paleochannel sandstone bodies are present. The siltstone was apparently deposited over the entire mined portion of the Sub-3 seam prior to migration of fluvial channels across the area. It is likely that the siltstone represents overbank deposition from a nearby major fluvial system that developed immediately after peat deposition. This overbank deposition probably caused the cessation of peat production in the swamp.

The overbank siltstone is generally unfossiliferous, with only one thin band of fossil bivalves and gastropods about 3 m (10 ft) above the seam. This fossil zone is observable only in larger roof falls. The siltstone is only slightly carbonaceous and is, for the most part, clean, hard, and brittle.

As mentioned earlier, it has the tendency to form arcuate, parallel fractures spaced from 3 to 20 cm (1 - 8 in) apart when subjected to high stresses in the immediate mine roof. Where such fractures occur, hazardous roof conditions may exist and the roof can be difficult to stabilize.

Of the various roof lithologies present in the No. 3 mine, overbank deposits of thinly bedded sandstone create the most treacherous roof conditions, particularly where the total overburden approaches or exceeds 600 m (2000 ft). These thin-bedded sand deposits generally accumulated along flanks of channel-fill sand bodies and, in certain instances, formed broad sheet sands of considerable lateral extent (figure 3). It is possible that these sheetlike sandstones represent a combination of levee and splay overbank deposition from numerous small fluvial channels that show as lenses in the mine roof.

These thin-bedded deposits range from about 10 cm to 2 m (4 in - 7 ft) thick where observed in roof falls and overcasts. Individual sandstone beds range from about 4 to 20 cm (2 - 8 in) thick, with local interlamination of siltstone and mudstone. The thin sandstone beds are commonly ripple laminated and in many cases climbing ripples are present, indicating rapid deposition. The sandstone of these overbank deposits is very fine-grained, well-sorted, moderately indurated, with a calcite cement. In general, grain composition of these sands is similar to the paleochannel sandstone bodies. Grain size, however, appears to be slightly finer.

Thin-section analyses of samples from overbank sandstones show that they are composed almost entirely of quartz, and that grains range from very fine- to fine-grained, with the very fine-grained portion dominating. Calcite forms the cement, with some clay and carbonaceous material included. Three samples were obtained for thin-section analysis, and the general grain size characteristics of the samples are tabulated in table 2. The 31-250 micron grain size dominates, and cumulative frequency curves of samples show their similarities (figure 5). All of the samples are well sorted.

Paleocurrent directions in the overbank sandstone deposits are most commonly in a direction away from adjacent paleochannel sandstone bodies (plate 1). This suggests that the thin-bedded sandstone units most likely had their sources in fluvial channels and were deposited as splays of overbank flooding from the channels. Flow directions were readily determined from well-preserved ripple marks. Bioturbation is also common at the base of the thin-bedded sandstone layers, particularly at the contact of the overbank sandstone with the underlying overbank siltstone.

It is uncertain, due to the limitations of in-mine observation, whether the deposits represent levees or splays. Well-developed levee deposits are poorly known or, at least, are not well documented in the lower portion of the Blackhawk Formation in the mine area. Moebs and Ellenberger (1982) use the term "crevasse splay" in a non-genetic descriptive sense for thinly bedded sandstone deposits found in Appalachian coal mines. They describe these units as ranging from 2 to 9.3 m (7 - 30 ft) thick, laterally persistent, forming

Table 2. Grain size distribution in overbank sandstone samples

Sample No.	Micron Diameters					Number of Grains Counted
	500-250	250-125	125-62	62-31	31-16	
1	0	15	53	31	1	100
2	0	43	51	4	0	100
3	0	5	56	36	3	100

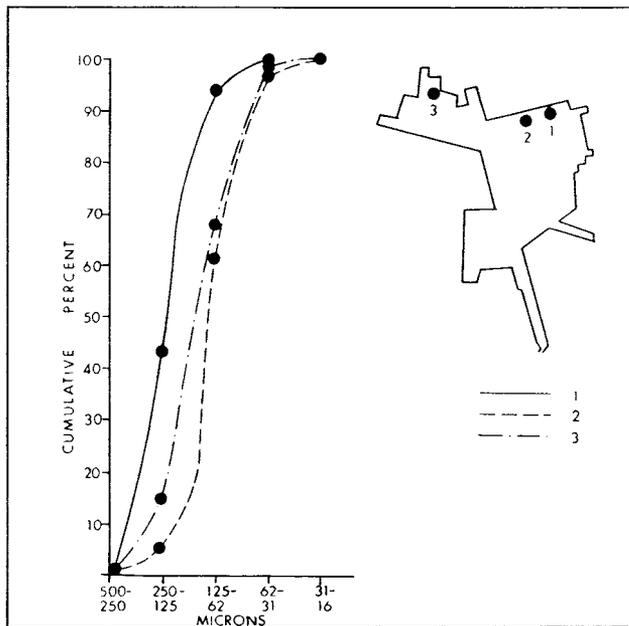


Figure 5. Cumulative frequency curves of three samples of overbank sandstone.

sheetlike to lenticular bodies. They are comprised of predominantly flat-bedded, laminated sandstone interbedded with shale. When these "crevasse splay" units lie within 2 to 3 m (7 - 10 ft) of the top of the coal bed, the mine roof may be adversely affected due to inherent weakness along the contact of the shale and sandstone laminae. A similar condition appears to exist with the overbank sandstone deposits above the No. 3 mine.

As mentioned previously, some of the most hazardous roof conditions in the No. 3 mine are produced by overbank sandstone deposits. The thinly bedded sandstone appears to delaminate and sag rather readily when subjected to high vertical and/or horizontal stresses in the mine roof. Also, during initial phases of roof sagging, the brittle overbank siltstone layer which immediately underlies the overbank sandstone commonly begins to fracture and fall away between roof bolts. In a few cases, entire bolted intervals of roof rock have fallen in these circumstances.

Overbank sandstone deposits may be more widespread in the mine roof than figure 3 indicates, since the siltstone caprock may be obscuring their observation. It is believed, however, that where such overbank sandstone is present in

the immediate roof, the siltstone most commonly delaminates from the sandstone and falls away, exposing the sandstone layers. After observing roof bolting operations in various parts of the mine, it is apparent that thin, isolated layers of sandstone (up to 20 cm or 8 in thick) are quite common but, for the most part, these layers are thinner than the better developed overbank sandstones which originated from the fluvial channels and which do not adversely affect mine roof conditions.

In summary, the overbank deposits of the No. 3 mine have the following characteristics:

1. Overbank deposits of siltstone (called "caprock") generally form excellent roof conditions where they are not associated with channel-fill sandstone bodies or overbank deposits of sandstone.
2. Overbank siltstone immediately overlies the Sub-3 seam throughout the entire mined portion, except where removed by channel scour.
3. Overbank sandstone deposits are characterized by thin, horizontally bedded, very fine- to fine-grained sandstone which may show considerable lateral continuity.
4. The thinly bedded sandstones may reach thicknesses over 2 m (7 ft) and generally formed along flanks of channel-fill sandstone bodies.
5. Ripple lamination is characteristic of the thinly bedded overbank sandstone, and bioturbation is common at its contact with the underlying siltstone "caprock."

Swamp Facies: Swamp facies in the immediate mine roof generally consist of rider seams of coal and associated carbonaceous mudstone interbeds. The rider seams above the Sub-3 seam in the No. 3 mine area are 10 to 30 cm (4 - 12 in) thick. These thin coal seams commonly split from the thick mineable portion of the Sub-3 seam at some point with the appearance of a rock parting or "split" in the upper part of the coal bed. This rock parting usually thickens away from the point of its appearance in the coal seam until the interval between the main seam and the upper "split" of coal increases to as much as several meters. The rider seams of coal in the No. 3 mine, although difficult to map except in roof falls and overcasts, appear to be rather lenticular in nature, not extending more than 50 to 60 m (165 - 200 ft) in most cases.

Because the rider seams were difficult to map in an underground setting and because they do not adversely affect the roof in the No. 3 mine, their locations are not included in plate 1. Petranoff and others (1981) indicated that rider

seams in an underground coal mine in Wyoming do not generally affect the mine roof when they are located within the roof-bolted interval, but when they lie in the 1.8 to 3.1 m (6 - 10 ft) interval above the roof bolts, adverse conditions may exist. I observed no adverse effects from rider seams in the No. 3 mine, regardless of their position in the roof strata. The reason for this is uncertain, but it is logical to assume that the rider seam contacts would constitute planes of uncontrolled weakness where a rider existed above the roof bolt interval. However, no evidence exists in the No. 3 mine to suggest that riders were the cause of any roof failures.

Roof Fall Classification and Description

Unstable roof conditions in the No. 3 mine, initiated by high stress around the mine opening, appear to be closely related to the various depositional facies present in the mine roof. It has, in fact, been possible to classify the various types of roof falls in the mine according to their occurrence in roof strata of different depositional origins. No attempt is made with this classification to suggest that types of roof failures discussed in this study will also occur in other coal mines in the area. This scheme does seem to be useful for the No. 3 mine. It may be useful as a guide to classifying roof falls in other mines or in efforts to develop a universal classification.

Most occurrences of unstable roof in the No. 3 mine appear to be a result of inherent weaknesses within either the fluvial channel-fill or the overbank facies. High stress concentration around the mine openings is probably a major factor influencing roof behavior in these various type of roof stratification. Ground water in the immediate roof also has a profound effect on the relative strengths of the rock. Factors such as high stress and/or ground water seem to have greatest adverse effects within or near the fluvial channel and overbank facies.

Four genetic types of roof falls occur within the No. 3 mine (figure 6). Three of these are associated with specific depositional regimes and one appears to be essentially unrelated to roof geology or stratification. These four roof fall types include: 1) falls associated with channel-fill sandstone bodies, 2) falls associated with overbank sandstone deposits, 3) falls associated with overbank siltstone deposits, and 4) "cathedral-type" falls which appear to be unrelated to immediate roof geology. Each of these categories of roof failures will be referred to as type A, B, C, and D respectively.

Type A Roof Falls: Type A roof falls (figure 6A) are those which occur beneath fluvial channel-fill sandstone deposits. Figure 3 shows the mapped locations of type A roof falls within the No. 3 mine.

Falls of this type most commonly occur as slabs and blocks which delaminate from the base of fluvial channel sandstone bodies immediately after mining and before roof bolting takes place. Occasionally, delamination from the paleochannel base occurs over a longer time and slabs and

blocks of sandstone fall around the roof bolts (figure 6A). Delamination occurs along highly slickensided, clay-rich laminae within lower parts of sandstone channels. These slickensides were probably formed by differential compaction of thin mudstone laminae within the channel-fill sandstone body. The slickensides are obvious zones of weakness along which large slabs and blocks delaminate and fall.

In general, type A roof falls are relatively minor in the No. 3 mine. They fall almost immediately after cutting of the coal seam during mining. This presents little danger to mine personnel, in that roof bolting usually stabilizes the problem areas. Occasionally, however, some delamination and deterioration may occur after bolting, and large slabs and blocks may fall around the roof bolts. This situation does present a hazard to mine personnel and, for this reason, paleochannel deposits in the roof of the No. 3 mine should be monitored in high personnel-exposure areas and any loose slabs or blocks should be pried down or stabilized.

Type B Roof Falls: Type B falls (figure 6B) occur in overbank sandstone deposits and are perhaps the most common and one of the most hazardous types of roof failures in the No. 3 mine. The overbank sandstone is thinly bedded and commonly contains thin laminae of siltstone and mudstone. Delamination occurs readily at lithologic boundaries, allowing slabs to fall.

As with type A falls, type B falls occur most commonly at the time of mining, before the roof can be bolted. After the coal has been removed beneath the overbank sandstone, the roof sometimes sags, and sandstone slabs delaminate and fall away. Occasionally, slabbing from the roof occurs even after roof bolting (figure 6B). In some instances, larger blocks of the thinly laminated sandstone delaminate above the roof bolt interval, bringing down several rows of roof bolts.

The number of larger roof failures related to overbank sandstones increases with increasing overburden thickness. A high percentage of type B falls shown on plate 1 are located under overburden thicknesses that approach and exceed 600 m (2000 ft). Stress conditions associated with large amounts of vertical loading on the mine openings are undoubtedly a major contributing factor to delamination, sagging, and eventual failure of the thinly bedded overbank sandstone layers.

The most hazardous situation with overbank sandstone deposits occurs when roof bolts do not extend through the entire overbank sandstone interval. When this happens, delamination can occur above the roof bolt interval and the entire bolted section of roof strata can fall. To avoid this situation, roof lithologies should be carefully mapped and measured as mining advances beneath the sandstone layers. As long as the entire overbank sandstone sequence is included within the roof bolt interval, major type B failures are not likely to occur, but if the overbank sandstone sequence extends above the roof bolts, further measures should be taken to support the roof. Moebis and Ellenberger (1982) noted such occurrences in some Appalachian area coal mines.

Type C Roof Falls: Type C roof falls (figure 6C) occur in the overbank siltstone "caprock" that immediately overlies the Sub-3 seam in the mine. These falls occur where fractures form in the siltstone beneath channel-fill sandstone bodies or beneath sagging overbank sandstone layers. In both instances, closely spaced, parallel, concentric fractures form in the brittle siltstone and blocks delaminate and fall between the rows of roof bolts (figure 6C).

Falls of this type are relatively minor and commonly occur in combination with other roof fall types (plate 1). They do, nevertheless, represent an unsafe roof condition and must be closely monitored. The fractures generally form within a few days of initial mining and roof conditions

worsen until type C failure begins to occur. If roof conditions are carefully monitored, unstable blocks of siltstone can be pried down. Type C roof falls are often the forerunners of type A and B falls, and measures should be taken to properly stabilize such areas.

Type D Roof Falls: Type D roof falls include all failures which do not appear to be related to any specific depositional facies. These falls have a characteristic dome or "cathedral" shape and most commonly occur at mine entry intersections (figure 6D).

The exact causes of type D failures are uncertain. Only five such falls were mapped in the mine (plate 1). These failures seem to occur without warning and commonly

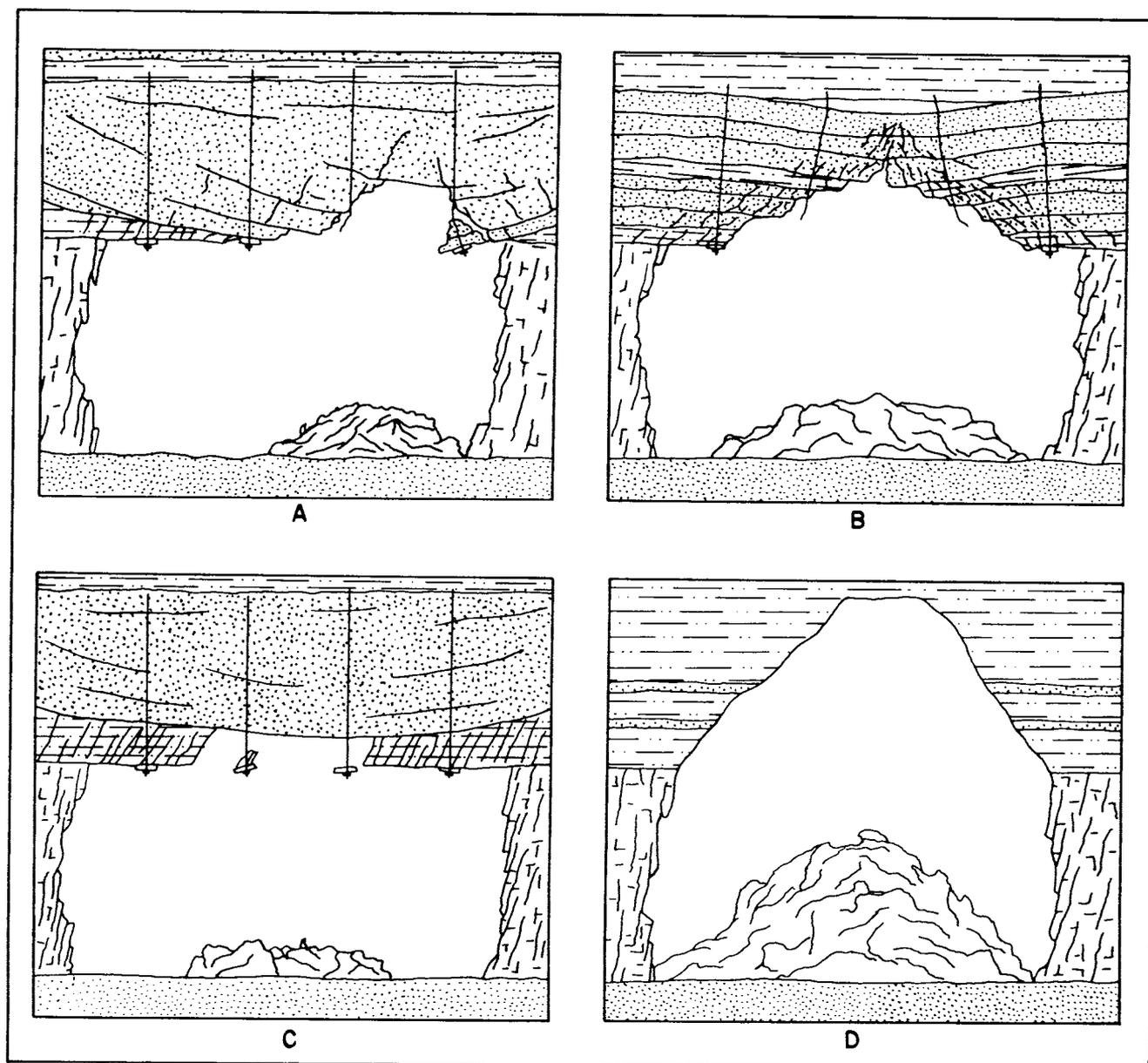


Figure 6. Generalized sketches of four types of roof falls occurring in the No. 3 mine.

extend upward to over 4 m (13 ft) into the mine roof. No obvious fractures or indications of high stress were observed, and they appear to have occurred regardless of roof lithology or stratification of beds. Peng (1978, p. 27) indicated that roof failures such as these are likely the result of high local shear stress. Further study and investigation of these types of failures in the No. 3 mine will be necessary to establish their exact causes.

Projected Roof Geology and Stability

With the use of abundant drill hole data in combination with in-mine mapping, expected roof conditions and lithology have been projected into unmined areas of the No. 3 mine lease area. An isosand map, indicating the percent sandstone in the 3 m (10 ft) of roof strata immediately above the Sub-3 seam, was developed from each core hole log (figure 7). For the purpose of this study, 0 to 30 percent sandstone was interpreted as overbank siltstone deposits, whereas 30 to 50 percent sandstone was interpreted to be overbank sandstone. A percentage of over 50 percent sandstone was interpreted to represent the channel-fill sandstone facies.

Although isolith or isosand contouring is by no means an exact representation of what will actually be encountered in the No. 3 mine, it does show the major depositional trends.

Because most unstable roof problems in the No. 3 mine occur near the paleochannel sandstone bodies or the overbank sandstone deposits flanking the channel sandstones, most geology-related roof control problems in future mining will likely occur in the projected areas. On the isosand map (figure 7) this includes all areas where the percentage of sandstone exceeds 30 percent. Within these areas, type A, B, and C roof falls appear most likely to occur and careful mapping and monitoring should be conducted as the mine advances to enable detection and necessary support of any potential unstable areas.

In the vicinity of projected paleochannel systems (areas in excess of 50 percent sandstone), other possible geologic problems may occur in addition to unstable roof. These include such problems as paleochannel scours or "washouts," coal seam rolls, and in-flows of ground water. Paleochannel scours can cause sudden, localized thinning of a coal seam, or even complete "washout" or removal of the seam. Although such occurrences are extremely rare in the No. 3 mine area, they are most likely to occur in the channel-fill zones. Coal seam rolls may not be directly caused by channel-fill sandstones, but it is not uncommon in the No. 3 mine to find channel bodies overlying coal seam rolls. Rolls generally have no major effect on mining in the No. 3 mine, but they do create occasional temporary difficulties for mining machinery that must negotiate the steeper

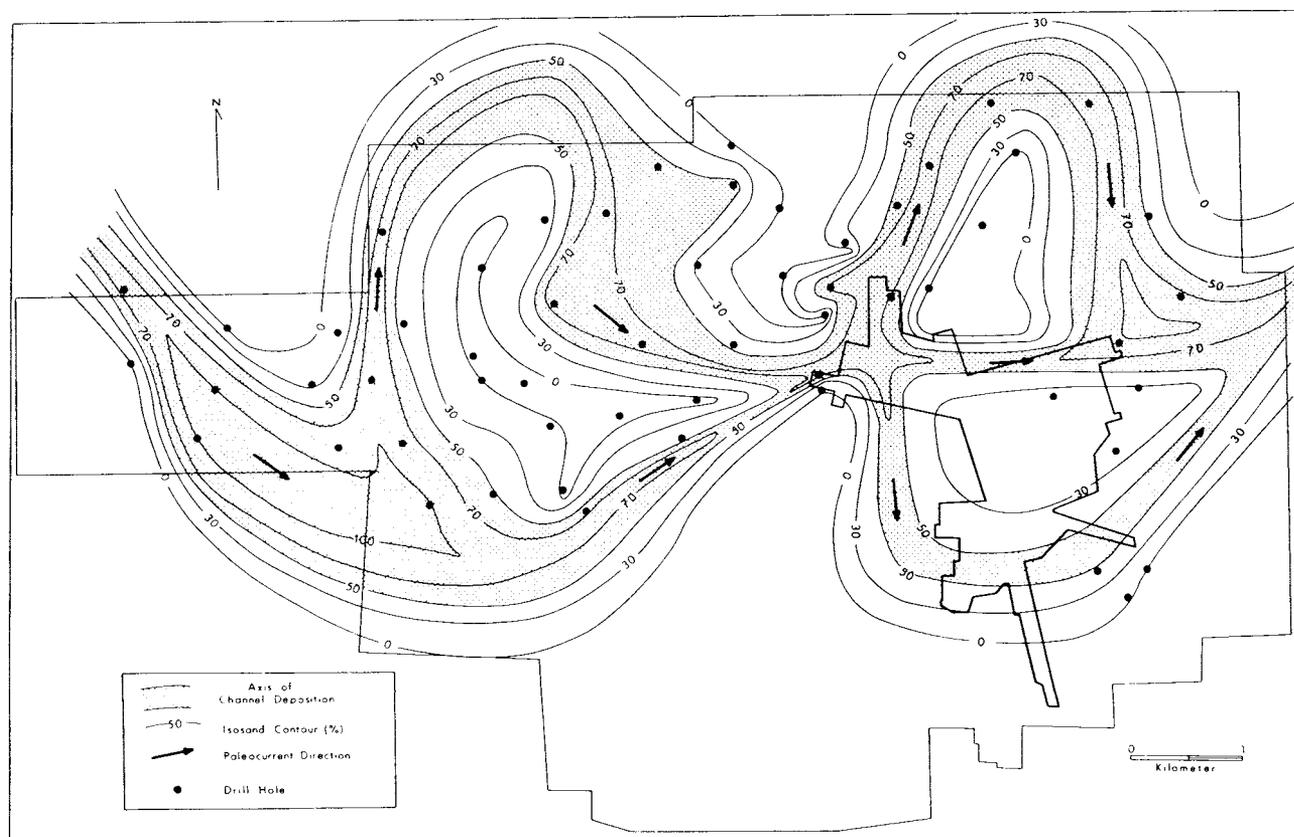


Figure 7. Projected roof geology map of the No. 3 mine lease area showing percent sandstone isoliths.

slopes. Because paleochannel systems often act as aquifers, increased flow of water into mine entries can also be expected within the projected channel-fill areas.

In areas where less than 30 percent sandstone is projected, it is likely that stable roof conditions will exist, and no major geology-related problems should be encountered. For the most part, the No. 3 mine has exhibited, and will continue to exhibit, good roof conditions. Only in localized areas will roof problems occur, and these problem areas will most likely be located within the plus 30 percent sandstone zones shown on the isosand map.

COAL SEAM CHARACTERISTICS

The Sub-3 seam is a high-volatile bituminous coal and is one of the major mineable coal seams in the No. 3 mine area. A portion of this study was devoted to detailed observation of the mined coal seam, including its megascopic and microscopic characteristics. An attempt was made to determine any coal seam characteristics which may be unique to the Sub-3 seam and to develop, if possible, a coal seam "signature."

To accomplish this, 73 stratigraphic sections were measured throughout the No. 3 mine, and major coal lithotype bands within the coal bed were described, as were cleat characteristics and rock interbeds. From this megascopic analysis, cross sections and coal formation graphs were produced for the existing mine workings (figures 8-9). Upon completion of the megascopic analysis, a microscopic analysis was conducted on polished coal columns and coal pellets from the Sub-3 seam (figures 11-12). Two polished columns were prepared from different localities within the mine, and polished coal pellets were prepared from two adjacent channel samples. The data from both the megascopic and microscopic analysis were then combined to determine if the Sub-3 seam exhibits any characteristics which give it a specific signature or which would serve to make it unique in any way with respect to other coals in the area. Such determination would prove useful for future coal seam correlations in the No. 3 mine area, as well as provide basic information on coal quality.

Megascopic Characteristics

Generally, the Sub-3 seam is a hard, vitreous, well-banded, and well-cleated bituminous coal. Resin is common in the coal bed, especially in certain lithotype bands. Calcite is present along cleat faces and fractures, and local pyrite is found in dull lithotype bands. One to three thin mudstone splits or partings occur within the coal bed within the extent of the mine workings. Two of the most distinctive features of the Sub-3 seam within the No. 3 mine are the well-developed lithotype bands and the well-developed cleat system. These features were studied in detail in an attempt to define qualities that are unique to the Sub-3 seam.

Lithotype Banding: Lithotype bands within the Sub-3 seam are well developed and laterally continuous. In order to delineate this banding, 73 stratigraphic sections were

measured to describe the major coal lithotype bands. Because coal seam description can be rather subjective, the following procedure was used:

1. Detailed sections were measured at 30 m (100 ft) intervals in selected mine entries to establish the lateral continuity of lithotype banding within the seam.
2. Once lateral continuity was established for distances up to 650 m (2000 ft), sections were measured throughout the entire mine at 160 to 260 m (500 - 800 ft) intervals.
3. The coal face at each measured section location was thoroughly cleaned to give good exposure of all lithotype bands.
4. A steel tape was secured to the coal face from roof to floor, and chalk was used to mark lithotype boundaries.
5. As suggested by Stach (1975) and Cameron (1978), all lithotype bands greater than 10 mm (0.4 in) thick were measured and described in detail.
6. Percentages of minor lithotypes (those less than 10 mm or 0.4 in thick) within each lithotype band were estimated with the use of charts prepared by Schopf (1960).
7. Face and butt cleat orientations were measured and described, as well as any fracture orientations in the immediate roof.
8. Roof and floor lithologies were described in detail.

Although there is a certain amount of subjectivity associated with the lithotype concept, it still provides a means whereby the internal bedded structure of a coal seam can be megascopically observed. Descriptions of lithotypes in the Sub-3 seam were made according to the International Committee for Coal Petrology Handbook (1963). Cameron (1978) summarized the descriptions as follows:

1. **Vitrain:** Very bright glassy bands or lenses, usually a few millimeters in width; thick bands are rare. Clean to the touch. In many coals vitrain is permeated with numerous fine cracks at right angles to stratification and consequently breaks cubically, with conchoidal surfaces.
2. **Clarain:** Bands of variable thickness having a lustre between that of vitrain and durain with striated texture and alteration of thin bright and dull laminae.
3. **Durain:** Grey to brownish-black, rough surface with dull or faintly greasy lustre, reflection is diffuse, markedly less fissured than vitrain.
4. **Fusain:** Black or grey, silky lustre, fibrous structure, extreme friability. It is the only constituent in coal which blackens objects with which it comes in contact.

All four of these coal lithotypes occur in the Sub-3 seam and were readily observable during measurement.

After megascopic description of the mined portion of the Sub-3 seam, data were compiled and coal formation graphs were constructed according to concepts first outlined by Tasch (1960), and later by Stach (1975) (figure 8). The coal formation graphs, in addition to giving a graphic means of portraying lithotypes within a coal seam, also indicate the

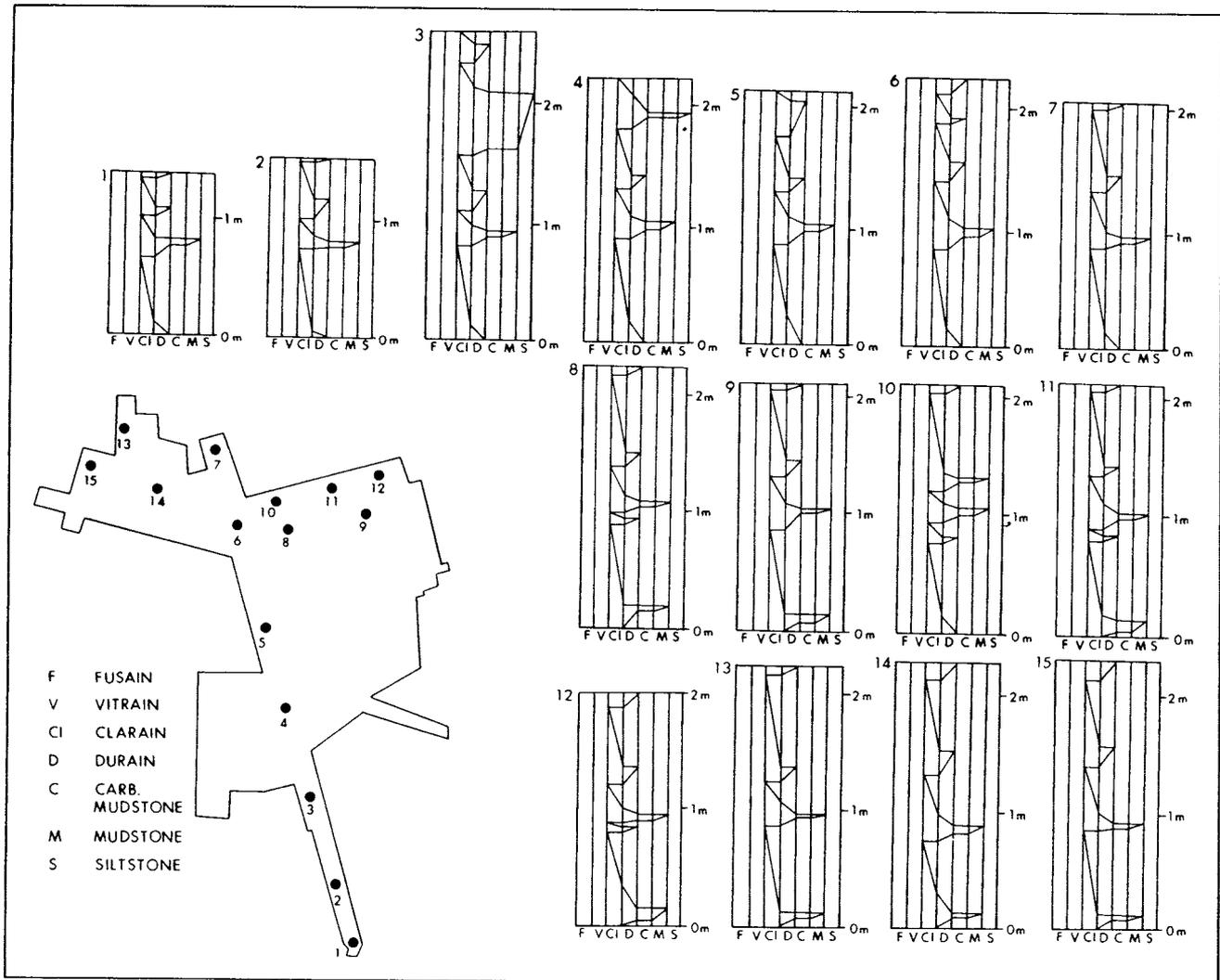


Figure 8. Coal formation graphs of the Sub-3 seam within the No. 3 mine.

relative "wetness" of the coal swamp environment at the time of deposition. Tasch (1960) indicated that the relative degree of wetness within a coal swamp is represented by the following lithotypes and lithologies (from driest to wettest conditions):

1. Fusain (driest conditions)
2. Vitrain
3. Clarain
4. Durain
5. Carbonaceous shale
6. Shale (wettest conditions)

This relative degree of wetness can also be viewed as a measurement of the relative rate of subsidence within the swamp, with the driest conditions representing slow to no subsidence, and wet conditions representing more rapid subsidence. Fusain would then be formed at low subsidence

rates and under shallow water cover with frequent access to air. Shallow flooding would result in the formation of vitrain and clarain, with deeper flooding resulting in durain (Stach, 1975). The deposition of carbonaceous shale and shale would require the wettest conditions or most extensive flooding.

As can be seen in figure 8, the formation graphs of the Sub-3 seam not only show that many lithotype bands are continuous throughout the mine, but alternating dry and wet conditions, or alternating rates of subsidence, are also indicated for the swamp in which the Sub-3 seam formed. These variations in swamp conditions must have occurred over relatively large areas within the swamp, giving the Sub-3 seam a rather distinctive "signature" (at least for the lateral extent of the mined portion of the Sub-3 seam).

Panel diagrams of the Sub-3 seam within the No. 3 mine show the laterally continuous nature of lithotype banding within the coal bed (figure 9). One of the notable features is

the tendency for carbonaceous mudstone and mudstone partings to have formed only within durain bands, or during what would have been the wettest conditions. It is not uncommon for durain bands within the Sub-3 seam to grade laterally into local mudstone or siltstone splits. In fact, a thick siltstone split (sections 1-4, figure 9) in the southern portion of the mine grades laterally northward into a thick durain band, which continues throughout the northern extent of the mine (figure 9).

In general, lithotype banding within the Sub-3 seam can be characterized by a predominance of clarain and durain bands, with clarain forming the thickest and highest percentage of bands. As expected in most bituminous coal seams, vitrain in the Sub-3 seam is abundant but only occurs as thin lenses and laminae up to 5 mm (0.2 in) thick, with only occasional lenses up to 15 mm (0.6 in) thick. Because vitrain laminae and lenses rarely exceed 10 mm (0.4 in) in thickness and are laterally discontinuous, none of the vitrain bands were described as individual lithotype bands during section measuring, even though a high percentage of the seam is actually vitrain. Local lenses of fusain are

also observable within the coal bed but, as with vitrain, fusain lenses are too thin and laterally discontinuous to be included as individual lithotype bands. Fusain lenses are commonly associated with brighter clarain bands and vitrain lenses, indicating drier swamp conditions.

Clarain bands in the Sub-3 seam can be described as mid-lustrous and striated, containing local thin lenses and laminae of vitrain and fusain. Resin commonly occurs in the bands as small blebs and as coatings along cleat faces. The striated texture of the clarain is created by alternating bright and dull laminae, with the brighter laminae composed of thin lenses of vitrain. Most of the Sub-3 seam is made of clarain bands ranging from 9 to 60 cm (4 - 24 in) thick. Occasional pyrite lenses and cleat fillings also occur in the clarain bands.

Durain bands in the Sub-3 seam can be described as dull and hard. They contain very few thin lenses of vitrain and clarain. Durain bands are generally thinner than most of the clarain bands within the seam, and many of the durain bands grade into carbonaceous mudstone and mudstone at some point within the coal bed. Resin appears to be less

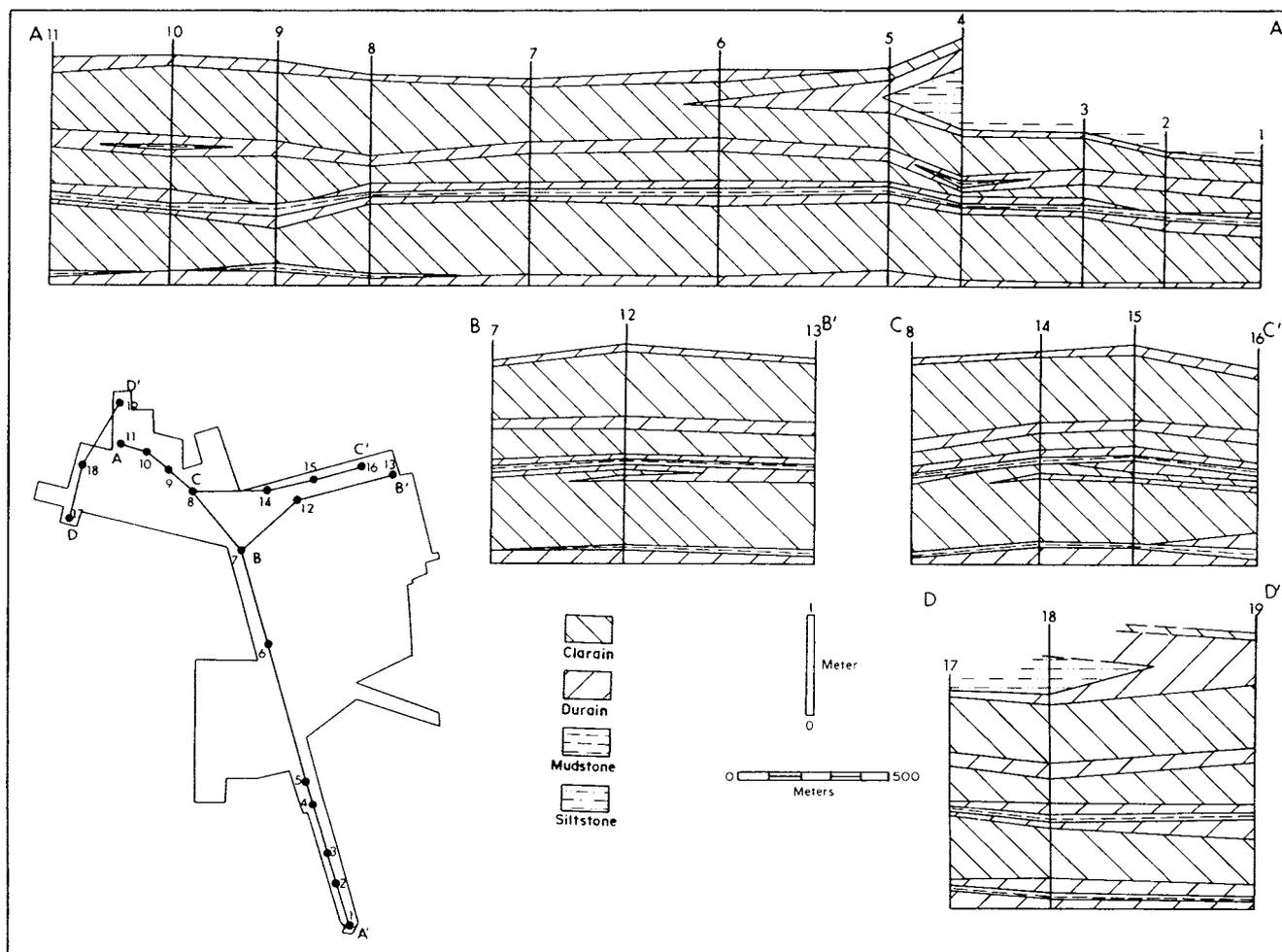


Figure 9. Panel diagrams showing lithotype banding and rock splits in the No. 3 mine.

common and, in most cases, is absent from the durain. The same is also true for megascopic pyrite, which only occurs in minor amounts in durain bands in the uppermost portion of the coal seam.

Vitrain, although the dominant constituent of the seam, does not occur in thick enough or laterally persistent bands to be considered a lithotype band. Most commonly vitrain occurs as discontinuous, thin, lenticular laminae within clarain and durain bands. These lenticular laminae usually reach a thickness of only 1 to 3 cm (0.4 - 1.2 in). The vitrain is very bright, vitreous, and contains numerous fine cracks or microfractures. Thicker vitrain lenses commonly exhibit conchoidal fracture.

Fusain occurs only in minor quantities and does not constitute a lithotype band within the seam. It occurs as lenticular laminae that range from 1 to 3 cm (0.4 - 1.2 in) thick and up to several centimeters wide, mostly in clarain bands. It exhibits a silky lustre and is usually soft and friable, with a "charcoal-like" appearance.

Lateral continuity of lithotype bands within the Sub-3 seam, particularly continuity of clarain and durain bands, indicates the potential usefulness of megascopic coal seam description in coal mines of this area. Not only does the Sub-3 seam exhibit a particular coal seam signature, but other coal seams in the area may have individual signatures as well. Such documentation may be useful for future coal seam correlation and environmental interpretations as well. Particular lithotype bands may be useful to miners as marker horizons when attempting to maintain a particular mining horizon in thicker coal seams. Lithotype banding could prove to be a valuable tool for geologic interpretation, as well.

Cleat: Cleat is a common feature of most bituminous coal beds. It is a natural joint system that occurs exclusively within coal seams, often independent of regional joint or fracture systems in surrounding strata (McCulloch and others, 1974). Cleat orientation and spacing does have some effect on mining. The frequency of cleat planes may determine the size consistency of mined coal; and cleat orientation relative to direction of mining may determine how easily the coal can be cut by mining machines (if mining is conducted parallel to the cleat, extraction is usually easier). Cleat orientation relative to mine entry orientation may also have some effect on rib stability. The cleat system may also act as a natural passageway along which coal bed gasses can bleed into mine entries.

The principal or best developed cleat orientation within a coal seam is termed "face" cleat. The secondary cleat orientation is termed "butt" cleat and found most commonly at right angles to the face cleat. Both face and butt cleat are generally well developed in coal seams of the Book Cliffs and Wasatch Plateau. The cleat system of the Sub-3 seam was easily measured within the No. 3 mine during mapping and section measuring.

Cleat orientation was determined with a Brunton compass at measured section sites within the mine. A total of 106 measurements were obtained and tabulated. Figure 10 is a rose diagram of the measured face and butt cleat

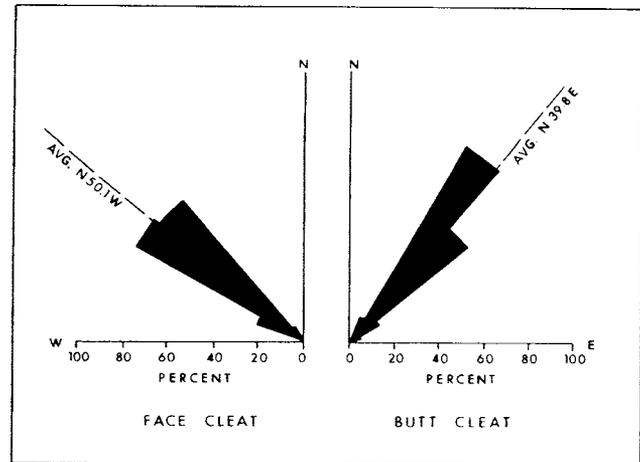


Figure 10. Percentage rose diagrams of face and butt cleat in the No. 3 mine.

strikes. The average face cleat strike is approximately N. 50 W. and average butt cleat is approximately N. 40 E., a 90-degree angle. Individual cleat planes are vertical with cleat spacing ranging from 1 to 1 cm (0.4 - 1 in) in vitrain and clarain bands, and 5 to 6 cm (2 - 2.4 in) in durain bands.

The origin of cleat in bituminous coal is uncertain. McCulloch and others (1974) indicated that three main theories of formation have been proposed. These include both a tectonic and nontectonic theory, as well as a theory incorporating both tectonic and nontectonic processes. The tectonic theory attributes cleat formation to tectonic forces, such as those that formed the folded Appalachian coal beds. McCulloch and others (1974) found, for example, that the face cleat exposed in many coal mines was nearly perpendicular to fold axes of local anticlines or synclines. The nontectonic theory attributes cleat formation to compaction and dehydration of the coal seam during coalification (Moore, 1932). Cleat may also form due to a combination of tectonic and nontectonic processes, a theory which is discussed in detail by Moore (1932).

The average cleat orientation in the Sub-3 seam appears to have no obvious correlation to local geologic structure, which includes several gently, north-south-trending anticlinal and synclinal structures to the east of the mine site. More measurements of cleat in surrounding Book Cliffs and Wasatch Plateau coal beds are needed before a relationship of cleat in east-central Utah coals to geologic structure can be determined. Regional jointing studies would also be helpful for comparison to cleat orientation.

Regardless of the origin of the cleat system in the Sub-3 seam, it does have a slight influence on mining conditions. Because the face cleat is oriented in a northwest/southeast direction, the northeast and southwest corners of coal pillars tend to slab and deteriorate much more readily than the other two corners. This may be an important consideration for pillar failure criteria in sections of the mine where pillars are being extracted. The cleat system also appears to act as a conduit for the transport of methane gas into mine entries

(data supporting this are presented later). As a consequence, cleat could be an important consideration for mine ventilation techniques and mine entry orientation.

Microscopic Characteristics

Microscopic characteristics of the Sub-3 seam include such features as the microlithotype and maceral content of the coal. These features were studied to gain a more complete understanding of the nature of the coal bed. Chemical analysis of the coal is also included as one of the microscopic characteristics.

Microlithotype Analysis: Following megascopic field description of the Sub-3 seam, microscopic analysis of observed lithotype bands was initiated with the use of equip-

ment at the Utah Geological and Mineral Survey coal petrography laboratory. The purpose of this dried petrographic study was to determine the general microlithotype content of each laterally continuous lithotype band within the coal seam in order to further characterize and define each band.

Two full coal seam columns were collected from different localities within the No. 3 mine. These columns were cut and polished in their entirety to provide two complete polished sections of the Sub-3 seam. The polished columns were then described megascopically and compared with the field description to ensure that there were no major discrepancies between them. Each lithotype band was studied and percentages of microlithotype groups within each band were calculated. Figures 11 and 12 show column locations and results of the analyses.

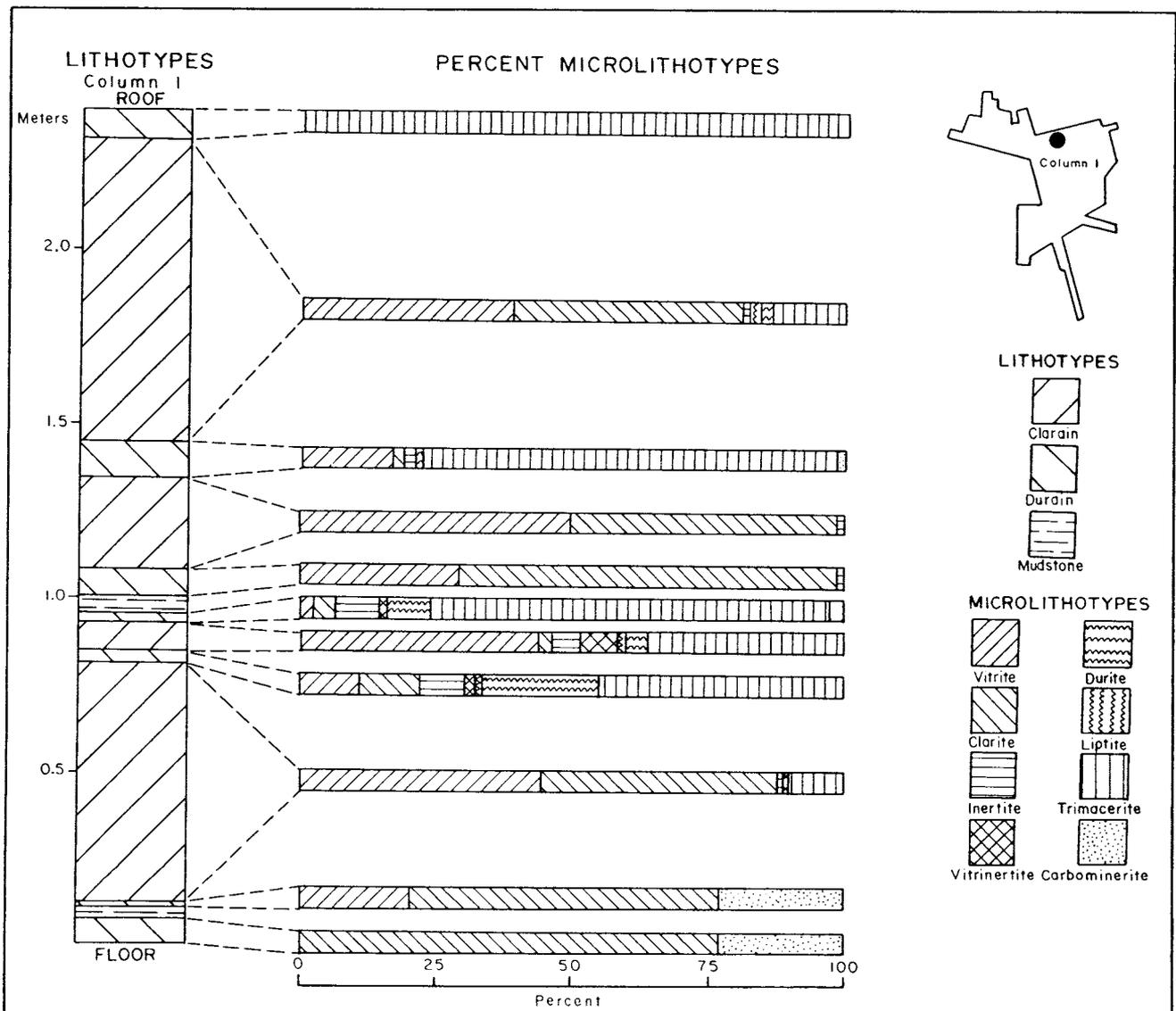


Figure 11. Microlithotype analysis of coal column I showing the percent microlithotypes in each lithotype band.

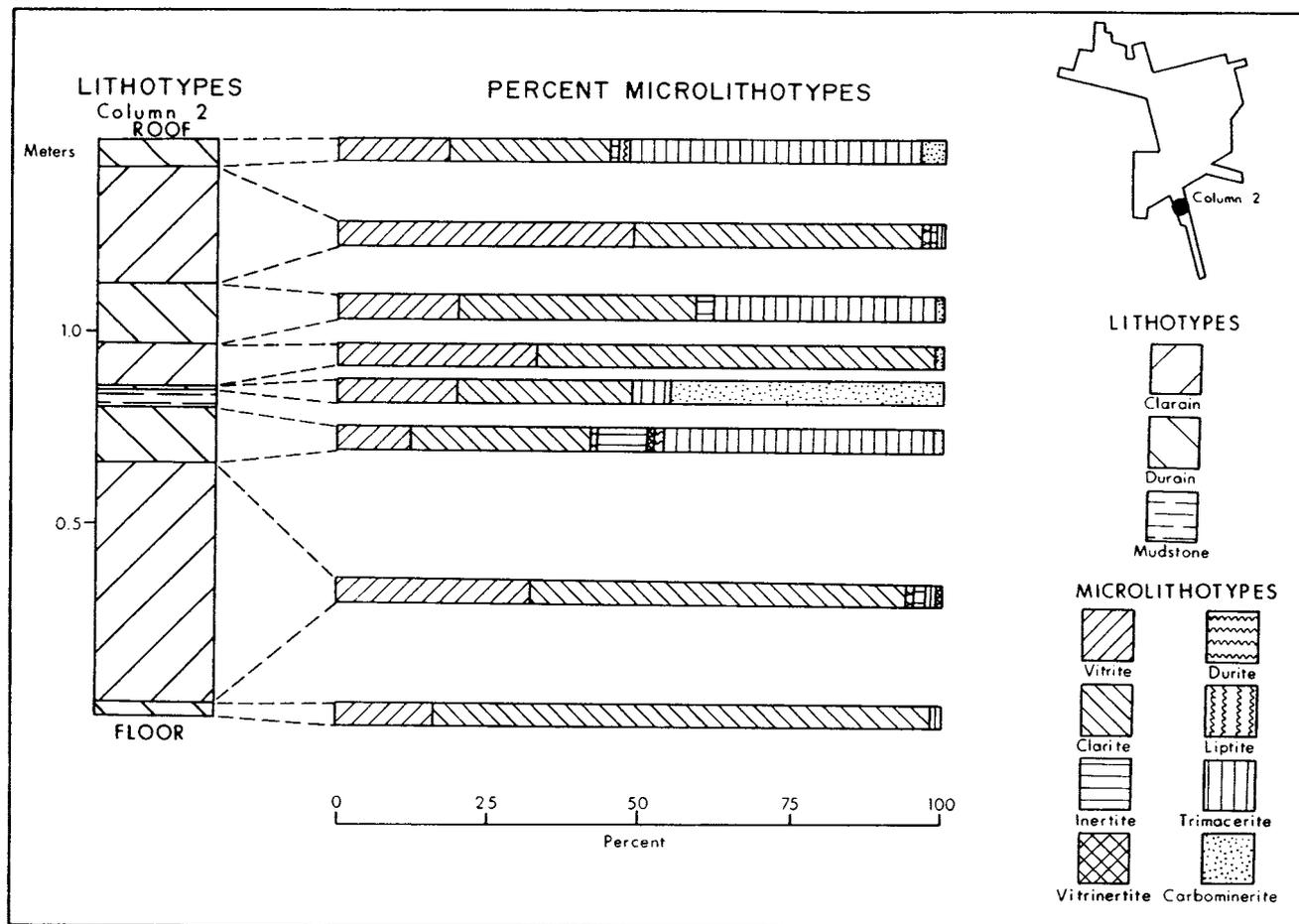


Figure 12. Microlithotype analysis of coal column 2 showing the percent microlithotypes in each lithotype band.

As described by Stach (1975), the microlithotype concept allows coal macerals within a column to be grouped microscopically into stratigraphic bands or units. Monomaceral microlithotypes contain one principle maceral constituent, whereas bimaceral and trimaceral microlithotypes contain two and three maceral constituents respectively. Table 3 gives the classification of the microlithotypes within these three major groups, as well as the maceral groups they contain.

Two conventions developed by the I.C.C.P., as outlined by Stach (1975), were followed during microlithotype analysis. First, only those bands 50 microns or more thick were recorded as individual microlithotype groups. Second, the so-called "5 percent rule" was followed, which states that a monomaceral or bimaceral microlithotype may contain up to 5 percent accessory macerals which are by definition not typical of the particular microlithotype. Because this was intended as a brief analysis designed to show any general relationships between microlithotypes in the polished columns and the lithotype bands in which they are contained, microlithotype identification was only taken to the "group" level.

Figures 11 and 12 show clarain lithotype bands contain high percentages of both vitrinite and clarite, with only minor

amounts of other microlithotype groups. Comparisons of the two polished columns show that percentages of microlithotype groups appear to vary laterally within correlative clarain bands. To determine the exact nature of microlithotype variation within the individual lithotype bands, many more columns of the Sub-3 seam would have to be studied.

Durain bands within the coal seam generally contain lesser amounts of vitrinite and clarite, with significant amounts of trimacerite, durite, and carbominerite (a microlithotype designation for layers of mineral matter). Minor

Table 3. Microlithotype classification

Maceral-Group	Maceral Composition	Microlithotype-Group
Monomaceral	Vitrinite—95%	Vitrinite
Monomaceral	Exinite—95%	Liptite
Monomaceral	Inertinite—95%	Inertinite
Bimaceral	Vitrinite + Exinite—95%	Clarite
Bimaceral	Vitrinite + Inertinite—95%	Vitrinerite
Bimaceral	Inertinite + Exinite—95%	Durite
Trimaceral	Vitrinite + Exinite + Inertinite	Trimacerite

percentages of liptite, inertite, and vitrinertite are also common. Like the clarain bands, percentages of microlithotype groups appear to vary laterally within individual durain bands.

In certain cases, particularly in the lowest durain band in each column (figures 11 and 12), the microlithotype analysis shows high percentages of clarite. It is possible that this lower durain lithotype band is actually a dull clarain rather than a true durain. Cameron (1978) differentiated clarain into bright clarain and dull clarain in bituminous coals of southern Illinois; it appears that this concept may be useful for Utah coals as well.

Because a thick siltstone split forms the mine roof at the column 1 location, column 1 does not represent as complete a section as column 2. Similarities still exist, however, between column 1 and the lower portion of column 2. It should be noted that all of the durain bands present in column 1 are present in column 2, at approximately the same horizon in the coal seam, and that the basal durain band is thicker and contains a thin mudstone split in column 2. This again shows the relationship between durain bands and rock partings or splits.

This occurrence of mudstone in a durain band illustrates the importance of lithotype and microlithotype banding studies. Durain bands, as mentioned previously, potentially grade into rock splits at some point within a coal seam. Many splits are localized and are not detected by surface drilling, but they can still result in serious coal quality dilution problems. As mining advances in a particular coal seam, durain bands could be monitored both megascopically and microscopically to observe any increases in mineral matter. This could feasibly aid in the prediction of splits in advance of mining, especially when coupled with surface drill hole information.

Maceral Analysis: In order to understand the general maceral content of the Sub-3 seam, a brief maceral and vitrinite reflectance analysis was conducted on polished coal pellets of the seam. The pellets were produced from channel samples taken adjacent to the two coal columns used for the microlithotype analysis. As with the microlithotype analysis, the polished coal pellets were prepared and analyzed at the Utah Geological and Mineral Survey coal petrographic facilities.

Vitrinite reflectance and maceral analyses were conducted according to A.S.T.M. Standards (1978). Utilizing this procedure, coal macerals were separated into the following subdivisions: vitrinite, exinite, resinite, micrinite, macrinite, semifusinite, and fusinite. Table 4 shows the results of the maceral inventory and vitrinite reflectance analysis of the two channel samples.

Vitrinite reflectance of the Sub-3 seam indicates a high volatile B bituminous rank, which is typical of many eastern and central Utah coals.

Chemical Analysis: Chemical analyses were run on the same channel samples that were used for the maceral analysis. Chemical analyses were done to further characterize the Sub-3 seam. Both proximate and ultimate analyses were conducted and are tabulated in table 5.

Table 4. Maceral inventory and vitrinite reflectance of two channel samples

	Sample 1 (%)	Sample 2 (%)
Vitrinite*	88.9	86.1
Exinite	4.1	3.6
Resinite	1.7	2.1
Micrinite	0.1	0.4
Macrinite	0.0	0.0
Semifusinite	1.9	3.5
Fusinite	3.3	4.3
Max. Mean Reflectance	0.68	0.71

*Pseudovitrinite included

The two samples, analyzed by Commercial Testing and Engineering Company, show significant differences in percent ash and sulfur, as well as in B.T.U. value. This discrepancy resulted because channel sample 1 consisted of coal from essentially the lower two-thirds of the Sub-3 seam, whereas sample 2 consisted of the entire Sub-3 seam. The percentage of coal to a thin mudstone split, which occurs in lower parts of both channel samples, is much less in sample 1 than in sample 2 (the difference between the two samples is readily apparent in figures 11 and 12). As mentioned previously, the coal at column or sample 1 site is much thinner due to a siltstone split that forms the mine roof at that point. The thin mudstone split that occurs throughout the entire No. 3 mine has a greater effect on the quality of the thinner coal.

Chemical and maceral analyses show slight differences in rank between sample 1 (12553 dry basis B.T.U.) and sample 2 (13266 dry basis B.T.U.). This is also manifested in a lower vitrinite reflectance in sample 1 (0.68) than in sample 2 (0.71).

MISCELLANEOUS GEOLOGIC FEATURES

A number of miscellaneous geologic features which affect both mine roof and coal seam characteristics, to some degree, are associated with the stratigraphy, depositional environments of the immediate roof, and the general Sub-3 seam characteristics. These features include such things as clastic dikes or "spars," rock splits or partings, coal seam rolls, coal bed methane, and oil seeps. In a geologic sense, some of these features are better understood than others but, since they do affect roof and coal conditions within the mine, they warrant documentation and brief discussion.

Clastic Dikes or "Spars"

"Spar" is a local miner's term used to describe sinuous, moderately to steeply dipping clastic dikes that occur in coal beds of the area. Spars occur in many of the coal seams of the Book Cliffs and Wasatch Plateau coal fields, with one of the best documented cases occurring in the Trail Mountain mine, about 60 km (37 mi) south of the No. 3 mine. Doell-

**Table 5. Proximate and ultimate analyses of two channel samples
(AR-as received, DB-dry basis, and MAF-moisture ash free)**

		Proximate analysis							
		%Mois.	%Ash	%Vol.	%Fix. carb.	B.T.U.	%Sulf.		
Sample 1	AR	2.48	12.16	40.90	44.46	12242	0.75		
	DB		12.47	41.94	45.59	12553	0.77		
	MAF					14341			
Sample 2	AR	2.03	9.33	41.57	47.07	12997	0.47		
	DB		9.52	42.43	48.05	13266	0.48		
	MAF					14662			
		Ultimate analysis							
		%M.	%C	%H	%N	%Chl.	%S	%A.	%O
Sample 1	AR	2.48	68.34	5.08	1.30	0.00	0.75	12.16	9.89
	DB		70.08	5.21	1.33	0.00	0.77	12.47	10.14
Sample 2	AR	2.03	71.97	5.44	1.50	0.00	0.47	9.33	9.26
	DB		73.46	5.55	1.53	0.00	0.48	9.52	9.46

ing (1977) found that spars in the Trail Mountain mine (Hiawatha seam) were largely composed of well-indurated, fine-grained sandstone, containing a high percentage of quartz grains cemented by calcium carbonate. Their thicknesses may range from a feather edge to more than 1 m (3 ft), and they commonly extend for great lateral distances within the mine, cutting across several entries or crosscuts.

Spars observed in the No. 3 mine have similar characteristics to those described by Doelling and others (1979). Generally, spars occur as linear features which trend from northwest to southeast, and locally from west to east. The spars usually extend in sinuous pattern from roof to floor and are vertically and horizontally discontinuous. Figure 13 contains sketches of spars observed in the No. 3 mine.

Because the Sub-3 seam overlies the massive Spring Canyon Sandstone, it was difficult to determine whether the spars originated from the floor or from the sandstone deposits in the immediate roof. In an attempt to determine this, samples were obtained from the marine sandstone in the floor, from spars within the coal seam, and from fluvial sandstone in the immediate mine roof above the spars. Thin sections of these samples were prepared and studied. Figure 14 compares the grain size distribution of the marine sandstone, spar, and overlying fluvial sandstone. It is readily apparent that the grain size distribution of the spar sandstone is quite similar to the fluvial channel sandstone, indicating that the spar had its source in the sands deposited above the coal bed.

The cause of the injection of the sand spar into the underlying peat deposit is uncertain. Doelling (1979) proposed a "dessication" model for spar formation in the Trail Mountain mine. In this model, the peat and its overlying blanket of sand and mud are first deposited. As more and more sediment is deposited, slight synclinal folding occurs and,

at the same time, the peat begins to dry and dessication cracks form. Unconsolidated sand from above then fills the cracks. Through time, the peat is coalified and volume loss occurs, and sand in the dessication cracks is folded sigmoidally. Sand from the spar is also injected horizontally into fractures opened at the margins of the spar.

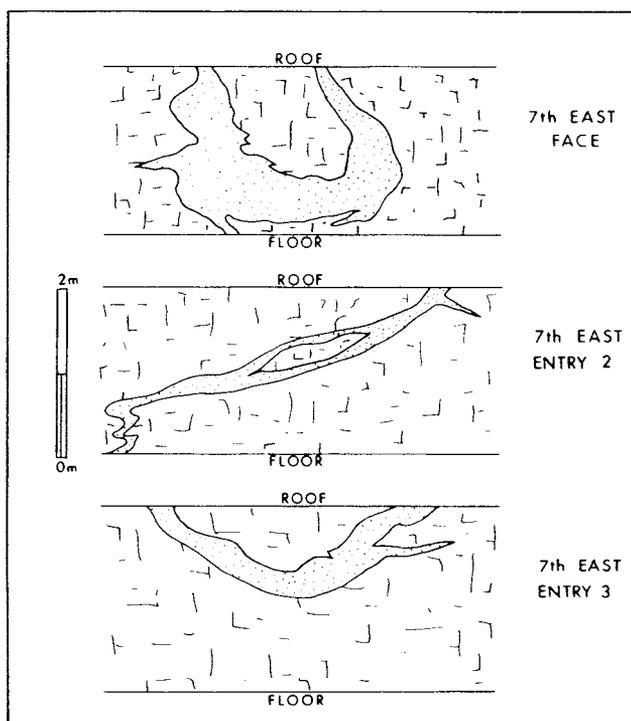


Figure 13. Generalized sketches of sandstone spars.

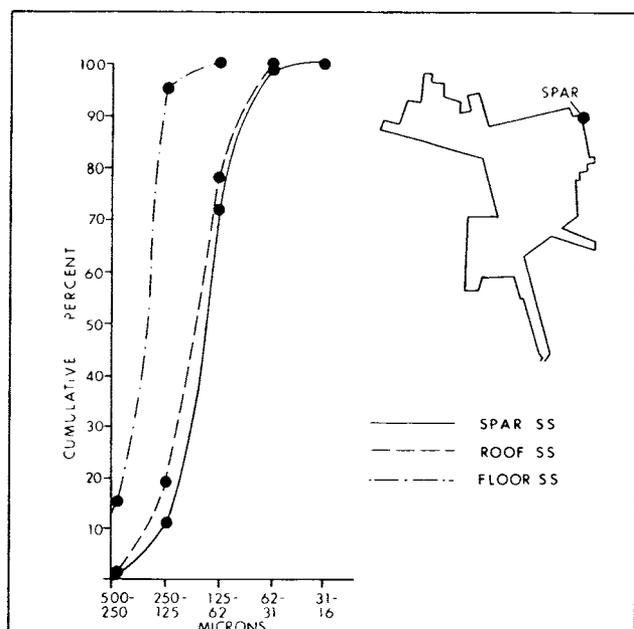


Figure 14. Cumulative frequency curves comparing a sandstone spar, a channel sandstone in the roof, and the beach sandstone in floor.

Another model, more related to tectonic events at the time of deposition, is suggested by spar occurrences in coal seams of the Scofield, Utah area, about 15 km (9 mi) southwest of the No. 3 mine. Spars observed and mapped by the author in Scofield area coal mines show orientations parallel to known regional fault trends. It is also not uncommon for spars to parallel vertical joint planes within the coal beds and the overlying rocks. This suggests that the same tectonic forces which created the faults and joints well after coalification of the peat and lithification of the surrounding strata may have been active even at the time of deposition. If this is true, the spars could have been injected due to liquefaction of the sand during earthquakes or some other tectonic activity. For this model to work, fractures would have had to form in the peat during such a tectonic event. It is uncertain, of course, whether such fractures can or do occur in peat beds during tectonic events such as an earthquake.

Whatever the origin of spars, they do appear to have originated from fluvial sand immediately overlying the peat, and they do occasionally cause problems to mining, particularly when their thicknesses exceed 25 cm (10 in). When this occurs, coal cutting machines, such as continuous miners or longwall shears, are hampered by excessive bit wear. In certain cases, if the spar is thick enough, more conventional methods of drilling and blasting have to be used, causing temporary production delays.

At the present time, prediction of spar occurrences in advance of mining is not possible. More regional studies of spars must be conducted in area coal mines in order to better understand their occurrences, modes of emplacement, relationships to various depositional settings, and overall predictability in advance of mining.

Splits

The term "split" is a mining term used to describe rock interbeds or partings that occur within coal seams. Splits are quite common occurrences in area coal beds and, if not previously encountered by exploratory drilling, may cause unexpected difficulties with coal cutting machinery, as well as dilution of run-of-mine coal quality.

Only one split of significant thickness has thus far been encountered during mining in the No. 3 mine. In fact, the No. 3 mine portals were driven beneath this split during initial mining. At the mine portal, the mined portion of the Sub-3 seam is 1.6 m (5.3 ft) thick and is overlain by 1.5 m (5 ft) of siltstone. This siltstone layer is in turn overlain by 21 cm (8 in) of coal, representing the upper portion of the Sub-3 seam. Northward (plate 1), the upper and lower portions of the Sub-3 seam eventually merge due to a gradual thinning and disappearance of the split, which significantly increases the thickness of mineable coal.

The pinchout line of the siltstone split has a northeast-southwest trend, indicating that the source area for the siltstone may have been to the southeast. The split could be the result of overbank deposition from a nearby fluvial system that flooded a portion of the coal swamp. The resulting siltstone is generally massive, hard, and shows only faint bedding characteristics. No fossils or burrowing are apparent, and there is a surprising lack of carbonaceous material. This may indicate that deposition of the silt may have been quite rapid, possibly in only one or two short-lived depositional events. Immediately after the silt was deposited, the swamp apparently re-established itself on the platform of silt now represented by the split.

Other minor splits occur in the Sub-3 seam which, for the most part, have had little, if any, effect on mining or coal quality (the coal is washed). One of these splits occurs throughout the entire No. 3 mine, making the Sub-3 seam within the mine area rather easy to recognize. This split is about 8 to 12 cm (3 - 8 in) thick throughout the mine and is composed of silty mudstone. It is located within the seam from 1 to 1.2 m (3.2 - 3.9 ft) above the sandstone floor. Figure 9 shows the laterally continuous nature of this split as well as locations of several other minor splits in the coal bed.

Coal Seam Rolls

The term "roll" is applied by local miners to large-scale undulations of an entire coal seam, including both roof and floor rock. Figure 4 is an illustration showing a typical roll in the No. 3 mine.

Many coal seam rolls, not only in east-central Utah mines but in numerous mines throughout the U.S., are the obvious result of differential compaction beneath large channel sandstone lenses (McCabe and Pascoe, 1978; Mercier and Lloyd, 1981). Because the Sub-3 seam immediately overlies a massive marine sandstone, however, it is questionable whether rolls within the seam are related to channel sandstone bodies, but they may be related to topographic undulations of the underlying beach sandstone. Differential compaction of a thick beach sandstone sequence

beneath a paleochannel would seem highly unlikely. If, on the other hand, the coal seams were deposited and compacted over an already undulating marginal marine sand or beach surface, coal seam rolls could occur without the presence of channel sandstones (as is the case for many rolls in the No. 3 mine).

More studies of coal seam rolls are needed to ascertain their origins and predictability, particularly rolls that occur in coal beds which overlie massive marine sandstone, as does the Sub-3 seam. If the rolls are the result of topography on top of marine sandstone, they may indicate the presence of tidal scour zones or beach ridges along the paleo-shoreline. Because channel-fill sandstone bodies do occur directly above many of the rolls (as shown in figure 4), it may be possible that distributary or splay channels actually followed topographic lows in the marine sand, even after peat deposition.

During mine mapping, an attempt was made to determine if the coal seam thickened or thinned within the roll area. If the roll was a result of a paleotopographic low, the coal which formed in that low should be slightly thicker than normal. Measurements of thickness were taken in 3 m (10 ft) intervals across two major rolls in the No. 3 mine and they show virtually no variation in seam thickness. This lack of change gives rise to further questions about the origin of the rolls, and much more must be known before attempts can be made to predict the occurrence of rolls in advance of mining.

Rolls observed in the No. 3 mine and mapped previously by mine surveyors show a general northeast-southwest trend. Because almost all of the rolls observed in the No. 3 mine occur in the longwall mining area in the northeastern part of the mine, determination of their lateral extent was difficult. Individual rolls extend laterally for at least 100 m (330 ft). It is likely that they extend even farther but at present this cannot be determined in the existing mine entries.

Rolls affect mining in several ways. The steep, irregular inclines of many rolls make it difficult for mining machinery such as continuous miners, longwall equipment, and haulage machinery to operate efficiently. Also, after mining, rolls often become areas where mine water collects and must be constantly pumped. A more adequate knowledge of the nature and origin of coal seam pools may, in the future, allow successful prediction of their occurrence and size in advance of mining.

Methane

Methane gas within coal beds in certain parts of the Book Cliffs and Wasatch Plateau coal fields has been well documented by Doelling and others (1979). The gas is a natural byproduct of coalification and occurs within specific "gassy" zones in the region, one of which includes the coal seams of the No. 3 mine area. In the No. 3 mine, as in any mine where methane is present, special safety precautions to detect and eliminate the gas during mining are of great importance.

Numerous locations were encountered during mine mapping where gas was bubbling up from the floor into pools of water. These pools provided excellent places for sampling

the gas and a total of four samples were obtained, utilizing specially designed vacuum bottles provided by the U.S. Bureau of Mines. The gas was collected by completely filling the bottle with water and then holding it upside down over the bubbles which were being emitted from the floor. As soon as the water in each of the bottles was displaced by gas, the bottles were sealed and carried out of the mine. Table 6 shows the results of gas chromatography analyses conducted by the U.S. Bureau of Mines on the four samples.

One of the interesting characteristics of the collected gas is the fact that every one of the samples contained nearly atmospheric proportions of oxygen and nitrogen. The nitrogen/oxygen ratio of samples 1 through 4 are 3.9, 4.2, 4.0, and 4.3 respectively. This compares to a 3.7 atmospheric nitrogen/oxygen ratio. The reason for this similarity is uncertain. Because the sample bottles were filled and sealed underwater, then analyzed in a controlled laboratory environment, it is unlikely that the samples were contaminated during sampling or analysis. It is possible that migration of atmospheric gases occurs along the cleat system in the coal bed and mixes with the methane. This may provide some supporting evidence for the conclusion that the cleat system in bituminous coal beds often acts to form a migration path for mine gases.

Because sampling of the gas was conducted from the sandstone floor, it is also apparent that coal bed gas migrates from the coal seam into the underlying marine sandstone and then back out into the mine entries. Some mixing of atmospheric gases and mine gases could also occur in the permeable sandstone.

Oil Seeps

An active oil seep occurs in the western part of the No. 3 mine where oil drips from the base of a channel-fill sandstone body. It forms large pools on the mine floor beneath the channel. Figure 15 shows the relationship of the seep to a paleochannel-fill.

The oil appears to be of relatively good quality. It is quite fluid and drips readily from the base of the channel sandstone. I observed a similar oil seep dripping from a channel sandstone body during mapping of a coal mine in the overlying Castlegate "D" seam. Other occurrences are also known in the abandoned Royal mine, just northeast of the No. 3 mine.

The oil has apparently migrated into the paleochannel sandstone fills in localized areas and, where encountered, it has been a nuisance to the coal miners who must work beneath it. The petroleum odor is quite annoying within the confines of a mine entry, and has been known to pour quite profusely from roof bolt holes for short periods of time. If the pools of oil that collect on the floor are not removed from the mine, they also create a fire hazard. Because these oil occurrences are so rare (only one in the No. 3 mine), they are of little concern to the mining company.

CONCLUSION

Underground mapping in the No. 3 mine has shown that geology of the immediate mine roof has a profound effect

Table 6. Gas chromatography analysis of collected methane samples

Sample no.	Major component (%)						
	CO ₂	O ₂	N ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	I-C ₄ H ₁₀
1	.08	1.3	5.1	92.8	0.49	0.09	0.03
2	.16	1.32	5.52	91.3	1.03	0.36	0.09
3	.13	1.33	5.35	91.55	1.03	0.33	0.09
4	.58	1.45	6.17	91.57	0.18	0.04	44 ppm

Sample no.	Major component (%)			Trace component (%)
	N-C ₄ H ₁₀	I-C ₅ H ₁₂	N-C ₅ H ₁₂	
1	0.04	0.04	0.03	0
2	0.09	0.06	0.03	0
3	0.09	0.06	0.04	0
4	66 ppm	15 ppm	14 ppm	139 ppm

Sample no.	BTU/Ft. ^{3*}		
	Gross	Net	Specific gravity
1	955.0	860.0	0.59
2	961.0	866.0	0.60
3	963.0	866.0	0.60
4	931.0	838.0	0.59

*at 760 MM HG & 60° F

on roof conditions of the mine. Most of the roof instability encountered in the mine is related to paleochannel sandstone lenses and their associated overbank deposits of thin-bedded sandstone. By mapping these deposits in the mine roof and projecting them into unmined areas with the aid of surface drill hole data, potential areas of geology-related roof instability can be predicted in advance of mining.

In general, four types of roof falls have been differentiated in the No. 3 mine. These include: 1) falls associated with channel-fill sandstone bodies, 2) falls associated with overbank sandstone deposits, 3) falls associated with fracturing of overbank siltstone deposits, and 4) "cathedral" falls which appear to be unrelated to roof geology. Because three of these roof fall types show direct correlation with specific facies, depositional studies within the No. 3 mine should continue, as the mine advances, to enable mine geologists and engineers to more accurately predict roof characteristics in advance of mining.

Coal seam characteristics of the Sub-3 seam are typical of many bituminous coal beds in the Carbon County area. Measured sections within the mine show that lithotype banding within the seam is laterally persistent, and that mapping of lithotype bands could eventually prove useful for future coal seam correlation work, as well as for maintaining mining positions in thick coal seams. Microlithotype studies may be helpful for correlating lithotype bands, as

well as eventually determining their environments of deposition.

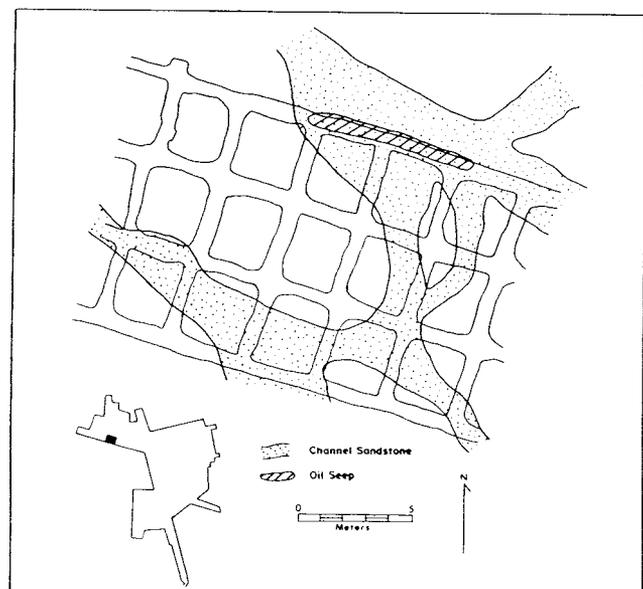


Figure 15. Mine map showing relationship of channel-fill sandstone in the roof to an oil seep.

Numerous other geologic features also affect mining conditions in the No. 3 mine. These include such things as clastic dikes or "spars," rock partings or "splits," coal seam rolls, coal bed methane, and oil seeps. Because many of these features are poorly understood, much more regional study of their occurrences in other coal mines of the Book Cliffs and Wasatch Plateau needs to be done.

Underground geologic mapping and analysis is important, not only for understanding roof and coal seam conditions within underground coal mines, but for prediction of geologic conditions in advance of mining as well. An understanding of depositional environments of rocks in the mine roof and their relationship to roof conditions can be gained by careful monitoring and mapping as mining advances. This understanding can be vital to mine safety and production, and proper measures can be taken to stabilize various types of unstable roof. Existing drill hole information can also be used to project expected roof conditions into proposed mining areas. Detailed in-mine study of coal seam characteristics can help in the prediction of coal quality as well as aid in the mining process.

ACKNOWLEDGMENTS

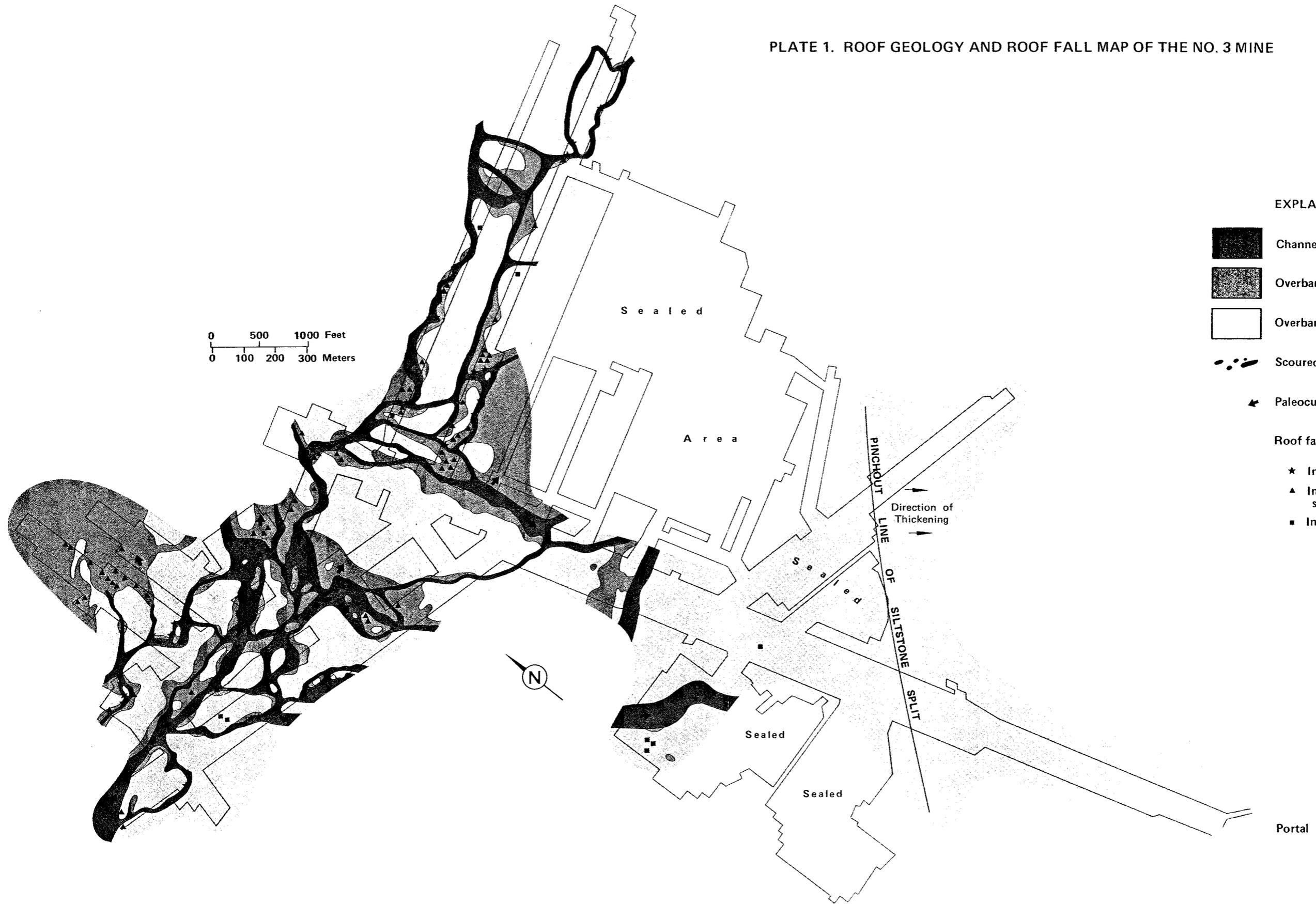
I wish to thank the U.S. Department of Energy and the Utah Geological and Mineral Survey for making this project possible. The support and advice of Mr. Archie D. Smith and Dr. Hellmut H. Doelling were invaluable. Alex Keith provided much needed field assistance and advice during underground mapping. I would especially like to thank the many mine company personnel who provided data and assistance, as well as access to the mine. I would also like to thank Dr. J. Keith Rigby. His advice, concern, and guidance during this project will always be appreciated. I am also grateful for the help of Dr. Lehi F. Hintze and Dr. Harold Bissell.

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PLATE 1. ROOF GEOLOGY AND ROOF FALL MAP OF THE NO. 3 MINE



EXPLANATION

- Channel fill sandstone
- Overbank sandstone
- Overbank siltstone

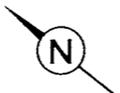
Scoured coal

Paleocurrent

Roof fall

- ★ In channels
- ▲ In overbank sandstone
- In siltstone

0 500 1000 Feet
0 100 200 300 Meters



Sealed

Area

Sealed

Sealed

Sealed

PINCHOUT LINE OF SILTSTONE SPLIT

Direction of Thickening

Portal

PETROLOGY AND GEOCHEMISTRY OF THE O.K. COPPER-MOLYBDENUM DEPOSIT, BEAVER COUNTY, UTAH

By Theodore W. Taylor¹

ABSTRACT

The O.K. deposit, located in the Beaver Lake Mountains of southwestern Utah, is a hydrothermal copper-molybdenum deposit hosted by a calc-alkalic quartz monzonite intrusion of Oligocene age. Primary ore minerals, chalcopyrite, molybdenite, and minor pyrite are concentrated in a pipe about 100 feet (30 m) in diameter composed of coarsely crystalline quartz. Minor occurrences of vein, disseminated, and fracture-filling mineralization are also present. Mining of high-grade ore pockets within the pipe prior to 1902 produced 1145 tons of ore averaging 40 percent copper, 7.5 oz/ton silver, and .18 oz/ton gold. Total production from the mine through 1974 was about 650,000 tons of ore containing about 7716 short tons of copper. No molybdenum grades are available.

Hydrothermal alteration of quartz monzonite around the mineralized pipe is represented by a series of concentric, nested alteration zones containing mineral assemblages similar to those found in porphyry stock work deposits. Silicic, quartz-sericite (phyllic), argillic, and propylitic alteration zones were identified, both mineralogically and geochemically.

Mineralization is interpreted to be most closely related to the low fluorine, plutonic, calc-alkalic type of stockwork copper-molybdenum deposits with many characteristics of magmatic-hydrothermal breccia pipes. Possible genetic models for the deposit are presented and exploration possibilities discussed.

INTRODUCTION

The O.K. deposit is a small copper- and molybdenum-bearing body of massive quartz hosted by quartz monzonite. It is located in the southern Beaver Lake Mountains, approximately 10 miles (16 km) northwest of Milford, Utah (figure 1), and is bounded by the San Francisco Mountains to the west, the Milford Basin to the south, the Rocky Range to the southeast, and the Beaver River Valley to the east and north. Access is provided by numerous dirt roads from Utah Highway 21 near Milford, Utah.

Discovery of the O.K. deposit was made in the 1870s and mining began in 1900 (Butler, 1913). Production was intermittent between 1900 and 1975. Early production, from 1900 to 1907, exploited a high-grade pod of copper-molybdenum

ore by underground methods. Early production, prior to 1902, consisted of 1145 tons of ore averaging 40 percent copper, 7.5 oz/ton silver, and .18 oz/ton gold (Butler, 1913). Underground workings totalled approximately 4500 feet (1371 m) in length and consisted of a shaft, an incline, and three levels at 200, 300, and 400 feet (61, 91, 122 m) (Butler, 1913). Exploration in the area resumed in the 1950s when the Bear Creek Mining Company became interested in the area and conducted a drilling program. In 1968, open-pit mining began at the O.K. deposit after a merger between the American Mining Company and the West Toledo Mining Company. Ore was treated by acid leach and cementation. In 1970, Shield's Development Company operated the O.K. Mine and in 1971 Essex International, Inc. took over operations. Essex operated the mine until it closed in 1973. Steven and Morris (1984) report that about 7 million Kg of copper and minor gold and silver were produced from the mine. Approximately 7,000 short tons of copper (635,000 tons of ore) were produced by open pit mining after 1970.

Early investigations in the area were conducted by B.S. Butler in the early 1900s (Butler, 1913; Butler, 1914; Butler and others, 1920). A study of the geology and ore deposits of the Beaver Lake Mountains was made by Barosh (Barosh, 1960). Geologic mapping of the Milford 15' quadrangle, which includes the O.K. deposit, was completed in 1979 (Lemmon and Morris, 1979) and the adjacent Beaver quadrangle was done in 1984 (Lemmon and Morris, 1984). A mineral resource potential study of the Richfield 1° x 2° quadrangle (Steven and Morris, 1984) was completed which provides a regional volcano-tectonic framework from which the O.K. deposit may be viewed.

The present study was undertaken to gain an understanding of the processes of mineralization and alteration which produced the O.K. deposit. Field work consisted of limited mine mapping and sample collection. A total of 47 samples from a .3 acre (1200 m²) were collected, encompassing both the O.K. and adjacent Beaver-Harrison deposits. Plate 1 shows sample locations in and adjacent to the O.K. pit. Drill cuttings

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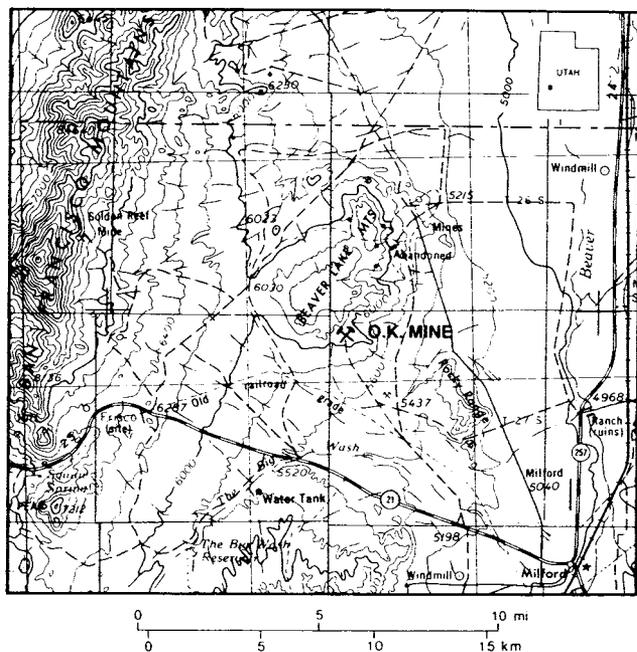


Figure 1. Location map of the O.K. Mine and vicinity.

from holes in the O.K. Mine were made available for this study. Drill samples were collected from horizontal holes at the 200-foot (61-m) level of the mine and are shown in figure 6. As an example of the sample numbering system, the sample number 20-110 designates that it was collected 110 feet (33.5 m) along drill hole no. 20. A total of 61 thin and polished sections were made from the collected samples.

This study was based largely on laboratory studies of samples collected from the O.K. Mine area. Methods used include petrography, x-ray fluorescence, electron microprobe analysis, x-ray diffraction, and fluid inclusion studies.

GEOLOGY AND STRUCTURE OF THE BEAVER LAKE MOUNTAINS

A geologic map of the Beaver Lake Mountains is shown in figure 2 (Barosh, 1960). In general, Paleozoic sedimentary rocks are dominant in the northern part of the range whereas Tertiary volcanic and intrusive rocks comprise the southern two-thirds of the range. Paleozoic rocks, dominantly dolomite and limestone, range in age from Cambrian through Mississippian. The Beaver Lake thrust fault is exposed at the northernmost edge of the range with Cambrian rocks of the upper plate lying to the north (Lemmon and Morris, 1984). Ordovician through Mississippian sedimentary rocks comprise the lower plate of the thrust south of the surface trace. Intrusive rocks of quartz monzonitic to granodioritic composition, of the calc-alkalic magma series, occur as two stocks, one centered near Smith Spring in the northern portion of the range, and the other, informally termed the O.K. stock (Lemmon and others, 1973), in the southern part of the range. The O.K. stock has been dated by K/Ar methods at 28.4 Ma (Lemmon and others, 1973).

Intrusive rocks are locally cut by swarms of aplite dikes. Volcanic rocks, which comprise broad areas in the central part of the range, are correlated with the Horn Silver andesite of Stringham and have been dated at 30.8 and 34.1 Ma (Lemmon and others, 1973). Flows range in composition from andesite to quartz latite with dacite being dominant. Sericitization and silicification of volcanic units are common along intrusive contacts.

A regional account of structural features, including the Beaver Lake Mountains area, was presented by Schmoker (1972). Using geophysical data, Schmoker concluded that the San Francisco, Beaver Lake, Rocky, and Star Ranges comprise a region underlain by a large, tabular Tertiary intrusion. From Schmoker's work, one may infer that the various stocks present in the Beaver Lake Mountains are cupolas of this large, deep-seated composite batholith.

DESCRIPTION OF THE O.K. MINE

The O.K. deposit is hosted entirely by equigranular quartz monzonite of the O.K. stock. Except along fractures, the stock is relatively free of alteration (Butler, 1913). However, alteration has been extensive in proximity to the O.K. deposit. Petrographic features of the mineralization are presented in a later section. At least three dikes cut the quartz monzonite host in the mine area, two of which are defined in this study and an aplite dike described by Butler from the O.K. mine workings.

A fissure system striking N80°W (figure 3) was noted by Butler (1913) and Barosh (1960) and appears to be coincident with a mineralized quartz-rich pipe in the mine area (figure 3). This fissure system is represented in the field by slickensided fault surfaces noted at several locations along the ramp of the O.K. pit. Strike and dip measurements of these surfaces reflect the general east-west trend. Faults are shown on the mine map in figure 6.

Primary ore minerals present in the O.K. deposit are chalcopyrite, molybdenite, and associated minor pyrite. High-grade mineralization was concentrated at the 200-foot (61-m) level of the mine in a pod with dimensions of 70 by 35 by 46 feet (21 x 11 x 14 m), located adjacent to the quartz-rich pipe (figure 4, Butler, 1913). Smaller areas of higher grade ore lie along the margin of the pipe (Butler, 1913). Disseminated chalcopyrite-molybdenite mineralization occurs as small veins of quartz and sulfides and as disseminated grains within altered quartz monzonite. Butler (1913) noted that disseminated mineralization lies within 50 feet (15 m) of the pipe and that disseminated ore values are generally highest in the veined zone adjacent to the pipe. Butler also observed disseminated mineralization in a relatively unaltered aplite dike at the base of the workings.

Secondary ore minerals observed in the field include malachite, azurite, chrysocolla, limonite, covellite, and cuprite. Secondary oxides and carbonates are generally absent beneath the 200-foot (61-m) level of the mine (Butler, 1913). A zone of sulfide enrichment underlies the oxidized zone in which covellite and chalcocite partly replace primary chalcopyrite and pyrite (Butler, 1913). Secondary alteration of molybdenite to powellite has been reported (Butler, 1913).

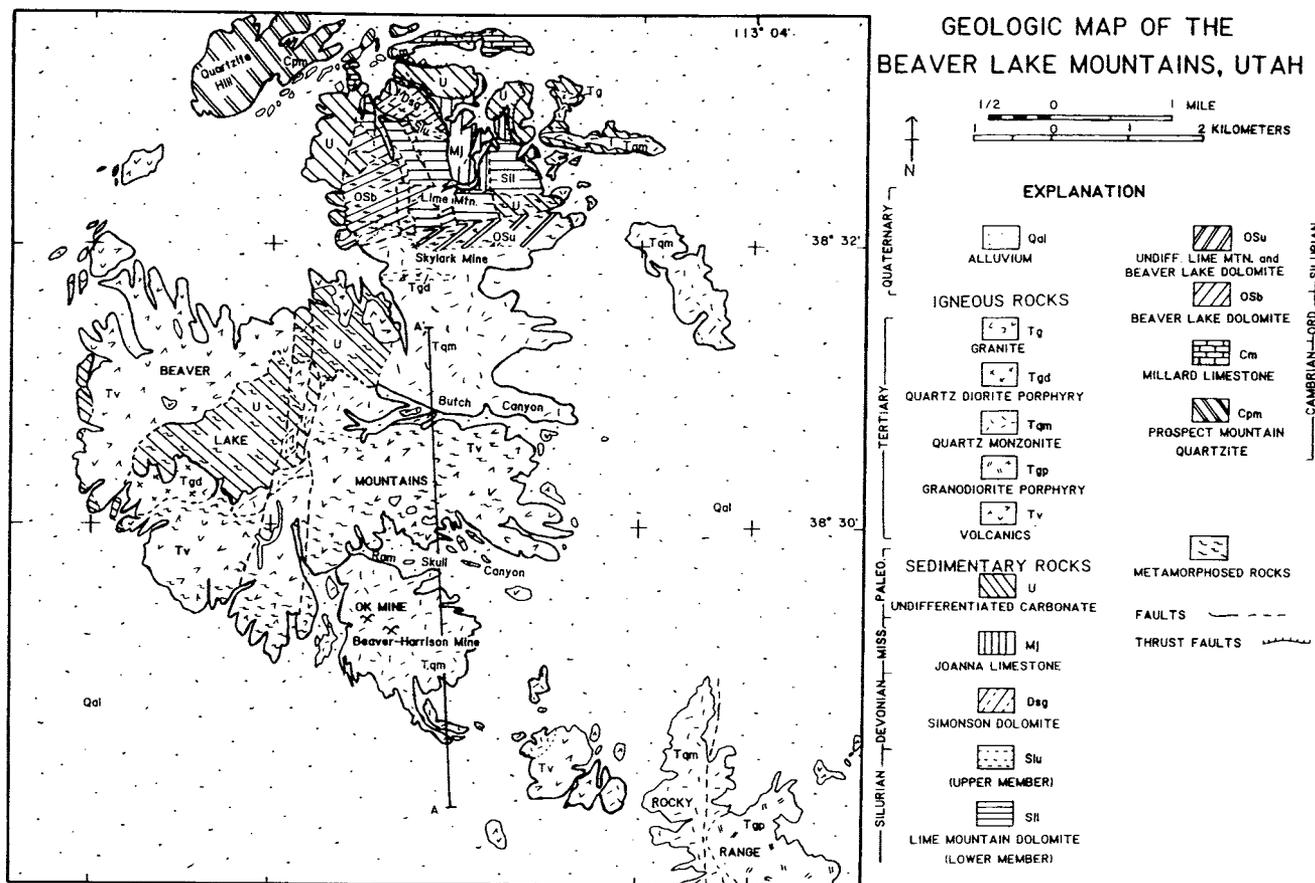


Figure 2. Geologic map of the Beaver Lake Mountains, Utah (from Barosh, 1960).

Gangue minerals present include quartz and sericite. Within the pipe the dominant mineral is very coarse, pegmatitic quartz. Cavities lined with coarse quartz crystals are common. Butler (1913) describes highly altered clasts of quartz monzonite toward the margin of the pipe, quartz monzonite being altered to quartz and sericite. Other minerals present in minor amounts in or adjacent to the deposit include kaolinite, chlorite, rutile, and rare tourmaline (Butler, 1913; this study).

Steven and Morris (1984) briefly described the O.K. deposit as "a nearly vertical pipe-like mass of breccia 60-65 m across in which pyrite, chalcopyrite, and molybdenite are disseminated through crackled quartz monzonite surrounding a silicified core." H. T. Morris (personal communication, 1985) mentioned having seen breccia textures at the center of the pipe-like body.

The Beaver-Harrison mine, located about 2000 feet (600 m) southeast of the O.K. deposit, also contains a coarse-grained quartz mass exposed at the top of the shaft. Tourmaline was noted along quartz grain boundaries during this study.

DESCRIPTIVE PETROGRAPHY OF THE O.K. MINE ROCKS

Compositional Variations

The O.K. stock is dominantly quartz monzonitic to granodioritic in composition. Sample locations where these

compositions were found include OC-4, OC-5, OC-7, OC-9, IC-4 to IC-9, and IC-11 (see plate 1). Amphibole, biotite, and chlorite together constitute approximately 15 percent of the rock. Amphibole is the dominant mafic mineral and constitutes 8 to 12 percent, and biotite 5 to 10 percent. Chlorite occurs in variable amounts depending on the degree of alteration. Quartz typically constitutes 10 to 22 percent and feldspar comprises roughly 65 percent of the rock with the abundance of plagioclase being either equal to or slightly greater than potassium-feldspar. Accessory minerals include magnetite, sphene, and apatite. Calcite and epidote occur in small amounts as alteration products of plagioclase and amphibole. Accessory and alteration minerals constitute as much as 5 percent of the rock.

Samples IC-2, IC-10, OC-3, OC-6A, OC-6C, OC-8, BD-1, R-8.3B, R-8.4, R-8.6B, R-8.8A, 20-110, 27-5, and 33-30 have a more granitic composition. Biotite, either partially or entirely altered to chlorite, is the dominant ferromagnesian mineral and constitutes 5 to 10 percent of the rock. The abundance of alkali feldspar, which appears to be greater than that of plagioclase, is difficult to assess due to extensive alteration of these samples.

Samples located between locations R-3 and R-8.2B contain even greater amounts of potassium feldspar relative to plagioclase, and quartz is more abundant. Biotite, partially altered to

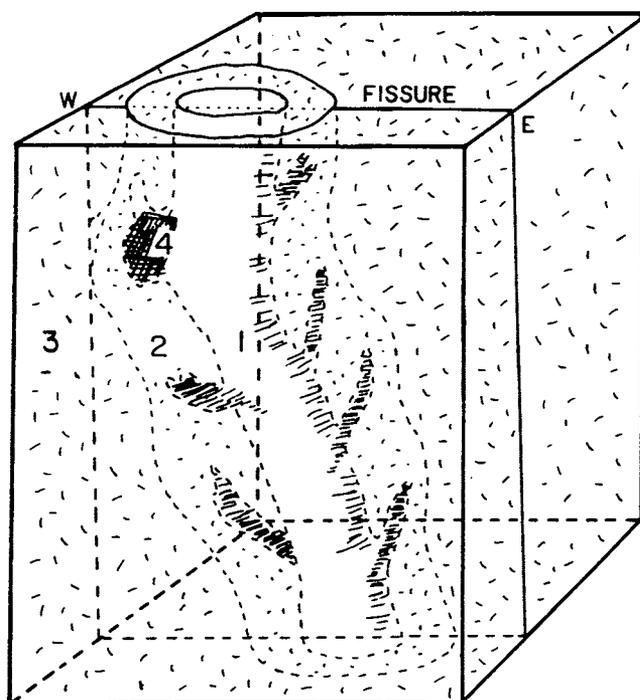


Figure 3. Generalized stereogram showing the relation of pegmatitic quartz and mineralized quartz monzonite in the O.K. Mine (from Butler and others, 1920). 1) Pipe of pegmatitic quartz, 2) altered quartz monzonite, 3) quartz monzonite, 4) high-grade ore.

chlorite, is again the only mafic mineral, but constitutes 10 to 15 percent of the rock.

Textural Variations

Holocrystalline and phaneritic textures of the O.K. stock are dominant with a fabric ranging from equigranular to seriate porphyritic. Plagioclase is euhedral to subhedral, whereas potassium feldspar is typically subhedral. These minerals range in size from coarse-grained phenocrysts (greater than 5 mm) to that of the groundmass (less than 1 mm). Groundmass consists of quartz, amphibole, biotite, and chlorite. Magnetite is fine grained, euhedral, and almost always found in granular aggregates with amphibole or biotite. Sphene is fine grained and anhedral, but commonly has sharp, distinct grain boundaries and fills the interstices between preexisting minerals such as feldspar. It usually occurs in groups of anhedral grains that are optically continuous, indicating that it is a late-forming, primary mineral. Calcite and epidote are very fine grained, anhedral, and usually associated with plagioclase or amphibole.

An interesting textural variation of the quartz monzonite lies between sample locations R-3 and R-8.2B. Occurring within this interval is the more granitic rock described above which has a poikilitic texture. Potassium feldspar occurs as relatively unaltered coarse-grained anhedral grains which completely engulf grains of moderately altered plagioclase, biotite, and/or quartz. Quartz occurs as coarse anhedral

grains or as granophyric intergrowths with potassium feldspar. The eastern margin of this poikilitic body appears to be gradational with equigranular rocks, a texture change suggesting that the poikilitic body developed as a large-stage crystallization product rather than being a later dike.

A post-alteration dike was tentatively identified which strikes NNE across the pit. The dike is fine to medium grained and equigranular with interstitial quartz in domains of optical continuity. Samples IC-4 and R-8 were collected from the dike (plate 1).

Another dike was tentatively identified and is represented by samples IC-2, OC-8, and BD-1 (plate 1). Groundmass in these samples is much finer grained than the quartz monzonite and imparts a more distinctly porphyritic appearance. This finer grained groundmass, mainly quartz with minor potassium feldspar, has a very distinctive, interlocking "jigsaw" texture.

Silicate Rock Alteration

In the following discussion, terminology used for hydrothermal alteration assemblages is taken from Mutschler, Wright, Luddington, and Abbot (1981) and Lowell and Guilbert (1970). These systems were adopted primarily for use in granitic molybdenite systems and porphyry copper systems, respectively. Figure 4 diagrammatically depicts hydrothermal alteration zonation at the O.K. deposit and should be referred to during the following discussion.

It is apparent from field and petrographic examination that the center of the alteration/mineralization system of the O.K. deposit is the coarse-grained quartz-rich pipe. This was documented by Butler (1913) who collected most of his information from underground workings. The silicic assemblage is interpreted to have originated by intense replacement of quartz monzonite breccia and by interstitial quartz precipitation.

Immediately surrounding the silicic core are highly sericitized and silicified rocks. Examples of this alteration include samples R-10.4, R-10.3, R-10.2, R-10.1, and R-9.1. This alteration zone may be termed the quartz-sericite alteration assemblage (Mutschler and others, 1981), or the phyllic zone of Lowell and Guilbert (1970). Primary feldspars have been entirely replaced by fine-grained mats of sericite. Quartz has been added to the rock and a minor amount of chlorite is present. Quartz occurs as both dispersed grains among sericite masses and as coarser grained vein material. Sample R-9.1, which is about 30 feet (90 m) from the silicic core, represents the maximum lateral extent of this alteration.

Away from the silicic core and up the pit ramp, the intensity of feldspar alteration decreases sharply as evidenced by sample R-9. Kaolinite was found (by x-ray diffraction) to be the major alteration product of feldspars starting at locality R-9 and continuing westward up the ramp. This kaolinite-bearing alteration assemblage is indicative of the argillic alteration assemblage.

A gradational boundary between argillic and propylitic alteration is present in the mine area. Following convention, the first appearance of secondary calcite and/or epidote associated with a feldspar or amphibole was chosen as the

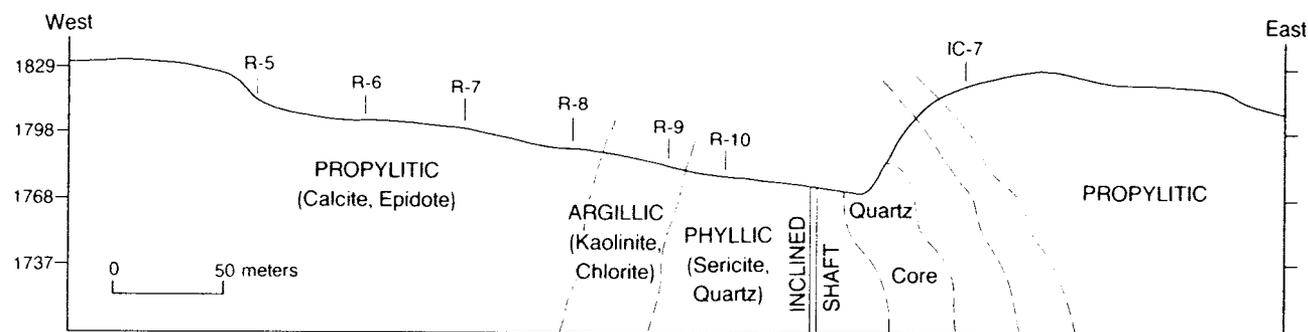


Figure 4. Diagrammatic cross section showing spatial relationships of the phyllic, argillic and propylitic alteration zones.

boundary between the zones. This occurs in sample R-8.4. Argillic alteration, then, occurs over a roughly 98-foot (30-m) wide interval between locations R-9 and R-8.4

Rocks of the OC and IC sample series have been propylitized, an alteration zone that was also documented by Barosh (1960). The commonly observed mineral association of amphibole (probably actinolite), chlorite, magnetite plus or minus sphene, epidote, calcite, and biotite is probably an alteration product of either original hornblende or pyroxene. In fact, this association most likely represents two stages of alteration. The original mineral was probably altered to actinolite and magnetite, with or without calcite and epidote. Then a second and less intense stage of alteration may have produced biotite, chlorite, and sphene from actinolite.

The final type of alteration to be discussed is that found in samples R-8.8B, R-8.7, R-5A, and R4. In hand specimen, these rocks have a greenish color due to evenly distributed, very fine-grained patches of chlorite. Feldspars have been altered to very fine-grained sericite. It is notable that samples R-8.8B and R-8.7 contain two of the three observed occurrences of disseminated chalcocopyrite at the O.K. deposit. This alteration is restricted to narrow bands (several cm wide) straddling fractures and may represent a late, less intense stage of alteration.

Hydrothermal alteration at the Beaver-Harrison Mine is similar to that at the O.K. Mine. A coarse-grained quartz mass is located near the top of the shaft Beaver-Harrison. Sericite and kaolinite were noted in other samples. Insufficient sampling was done here to identify alteration zonation.

Copper-Molybdenum Mineralization

Primary sulfide mineralization was found to be relatively simple, consisting of chalcocopyrite, molybdenite, and rare pyrite. Mineralization is spatially associated with the coarse-grained silicic core. Distribution of mineralization was discussed previously.

Few samples of ore material were collected in the field. Samples R-10.1, R-10.2, R-8.6A, and T-1 contain chalcocopyrite-bearing quartz veins. BD-1 contains chalcocopyrite along a joint surface with minor quartz. Samples T-2 and T-3 contain molybdenite disseminated in a quartz and feldspar gangue. Other pieces of coarse-grained quartz debris contain large grains and lenses of both chalcocopyrite and molybdenite. Finely disseminated chalcocopyrite was observed in minor

amounts in samples R-8.8B, R-8.7, and R-8A of the O.K. deposit and in samples OC-6A and OC-6C of the Beaver-Harrison deposit. The only observed occurrence of pyrite at the O.K. deposit was along a mineralized joint surface at site BD-1.

In thin section and in hand specimen, sample T-2 has an aplitic texture and contains only medium- to fine-grained quartz and potassium feldspar with disseminated molybdenite. In hand specimen, this aplitic rock exhibits a sharp contact with altered quartz monzonite, and it may represent the mineralized aplite dike reported by Butler (1913) and found below the 400-foot (122-m) level of the O.K. Mine.

Secondary Effects

Oxidation processes at the O.K. Mine, enhanced by the arid climate and abundant fractures and joints, have affected primary ore minerals, particularly chalcocopyrite. A zone of supergene sulfide enrichment, which occurs at or below the existing water table, was noted by Butler (1913) to contain secondary covellite and chalcocite but was not observed in this study.

In almost all of the samples of chalcocopyrite collected, thin veinlets of rusty-brown limonite, and less commonly malachite, occur as oxidation products within the chalcocopyrite. In polished section, cuprite and covellite were found associated with these limonite veins. This particular textural and mineralogical association is described by Ramdohr (1980) as a common oxidation phenomenon in chalcocopyrite and occurs in environments where pyrite is lacking (Jensen and Bateman, 1979; Titley, 1982).

MAJOR ELEMENT GEOCHEMISTRY

Geochemical data were collected so that trends in elemental concentrations could be delineated. Drill cuttings from horizontal holes at the 200-foot (61-m) level were used for whole-rock analysis. Samples were spaced at intervals of either 10 or 15 feet (3 or 15 m) along nine different holes and locations are given in figure 6. Samples collected in the field were also analyzed.

Geochemical data were acquired by x-ray fluorescence spectroscopy (XRF). Relative abundances of ten major elements, namely silicon, aluminum, iron, magnesium, potassium, sodium, calcium, titanium, phosphorus, and

manganese, were determined. Accuracy of elemental abundances are within two percent of the number listed, except silica which may vary up to four percent.

Very distinct trends are apparent in the distribution of potassium, sodium, calcium, and silicon. Trends in the other elements are either very weak or absent, and the copper distribution is especially erratic.

Distributions of potassium, sodium, calcium, and silicon abundances show an elongated, oval pattern which roughly parallels the long, east-west axis of the underground workings and present open pit. A strong, well-defined potassium high is found at the center of the mine area, with concentrations decreasing away from the workings out into the stock. The highest concentrations of potassium are adjacent to the silicic core. Silica concentrations coincide with the potassium concentrations, being high at the center of the mine area and decreasing outward. Sodium and calcium also have well-defined patterns but are inversely related to the potassium and silicon concentrations. These two elements are low at the center of the mine area and increase outward into the wall rock.

Enrichment in potassium, and corresponding depletion in sodium and calcium, reflects an increase in the amount of potassium feldspar relative to plagioclase and/or the development of sericite at the expense of feldspar minerals. By petrographic analysis, this high potassium concentration at the O.K. Mine corresponds to the quartz-sericite or phyllic assemblage alteration. Calcium, which was leached from the inner zones of alteration, was probably precipitated in the outer fringe of the system in the propylitic zone of alteration.

Water content of the rocks was determined approximately as the loss in weight during fusion (LOI) even though very minor amounts of sodium, sulfur, and carbon dioxide may also have been lost. Water content may be considered to be an indicator of the relative intensity of hydrothermal alteration. Rocks with the highest water content parallel the fault system shown in figure 6.

Based on the above geochemical observations, one may make some interpretations about the nature of the hydrothermal solutions. Given the enrichment in silicon and potassium in the center of the mine area, it may be inferred that the hydrothermal solutions were enriched in both potassium and silicon. Also, the abundance patterns of potassium, silicon, calcium, sodium, and water are all centered on, distributed symmetrically about, and elongate parallel to the east-west fracture zone mapped by Butler (1913) and shown on figure 6. More specifically, the patterns are centered on the silicic pipe. Thus, one may infer that the fracture zone, especially the silicic pipe area, served as the channelway through which solutions were being introduced to the O.K. Mine area.

FLUID INCLUSIONS

Fluid inclusions from samples R-10.1, R-10.2, R-8.6A, T-5, and T-6 of the O.K. deposit and OC-6D of the Beaver-Harrison deposit were examined. Primary fluid inclusions were divided into four types based on data from porphyry copper deposits. Nash (1976) suggested that four types of

inclusions are common in the porphyry environments. These are: 1) Moderate Salinity (Type 1); 2) Gas-rich (Type 2); Halite-bearing (Type 3); and 4) CO₂-rich (Type 4). The reader is referred to a paper by Nash (1976) for the characteristics and significance of each type. Samples from the O.K. Mine area contained dominantly secondary inclusions with relatively rare primary inclusions.

Qualitative Results

All samples contain inclusions of the Type 1 variety. Each of these inclusions contain a gas bubble which occupies 20 to 30 percent of the inclusion volume. Sample R-10.1 contains opaque daughter minerals in secondary inclusions which are probably magnetite, chalcopyrite, or pyrite. The presence of these ore minerals in secondary inclusions is significant because it may indicate that either primary magmatic fluids were not responsible for mineralization or, more likely, that there was more than one episode of mineralization.

Gas-rich inclusions (Type 2) are present in R-10.1, T-5, T-6, and OC-6D. The co-existence of these inclusions with liquid-rich Type 1 inclusions suggests that the liquids were boiling at the time of entrapment (Nash, 1976; Roedder, 1979). Halite-bearing inclusions (Type 3) are present in samples OC-6D and R-10.1 associated with gas-rich inclusions. Halite-bearing inclusions are also common in porphyry copper deposits (Nash, 1976). The presence of halite is also significant in that it indicates that the fluids were saline and that the chloride ion was present in abundance.

Quantitative Results

Using the fluid inclusion stage, the temperature at which ore-bearing fluids were trapped can be determined. To be able to draw statistically sound conclusions from filling temperature data, tens of inclusions from each sample should be analyzed. Unfortunately, primary inclusions were quite rare in the samples used in this study. Also, the presence of gas-rich inclusions invalidates filling temperature readings for reasons discussed by Roedder (1979).

After these considerations, reliable filling temperatures for only four primary inclusions were obtained and are listed in table 1. The temperatures ranged from roughly 250° to 350°C, within the range for hydrothermal fluids in a typical porphyry copper deposit (Nash, 1976).

Filling temperatures for secondary inclusions were determined to be in the range of 140° to 190°C. Their significance with respect to the overall ore-forming process is not certain, but they may suggest the existence of more than one episode of fluid transport and may be responsible in part for the mineralization at the O.K. Mine as evidenced by the daughter minerals in R-10.1.

DISCUSSION

A review of many deposit-type models has shown that the O.K. deposit cannot be uniquely classified. Three deposition models are applicable; porphyry copper, stockwork molybdenum, and magmatic-hydrothermal breccia pipe deposits. Comparisons between the O.K. Mine and each of these models will be made.

Table 1. Tabulation of quantitative fluid inclusion data.

Sample	Inclusion Description	Filling Temperature (°C)
R-10.1	Primary; Gas-rich, halite-bearing, and moderate salinity.	>350
	Secondary; Oriented with others along seams, contain opaque daughter minerals.	183.3
	Secondary; Oriented.	186.4
R-10.2	Primary; Moderate salinity.	298.2
	Primary; Moderate salinity.	274.9
	Secondary; Oriented, relatively small.	192.7
	Secondary; Oriented along seams.	150.1
LR-8.6A	Primary; Moderate salinity.	252.6
	Primary; Moderate salinity, relatively large.	261.3
	Secondary; Oriented along seams.	154.7
T-5	Primary; Gas-rich.	>350
	Secondary; Oriented along seams.	180.5
	Secondary; Oriented along seams.	184.2
T-6	Primary; Moderate salinity, relatively large.	318.6
	Primary; Gas-rich.	>350
	Primary; Moderate salinity	326.0
	Secondary; Oriented along seams.	183.4
OC-6D	Primary; Gas-rich and halite-bearing.	>350
	Secondary; Oriented along seams.	187.2
	Secondary; Oriented along seams.	183.6

In terms of tectonic setting, the area of the O.K. deposit is less ambiguous. Regional relationships, as discussed by Steven and Morris (1984), indicate that the 28.4 Ma O.K. stock (Lemmon and others, 1973) was intruded prior to the onset of Basin and Range extension. At this time, a broad magmatic arc, related to the subduction of the Farallon plate, was active in Utah (Westra and Keith, 1981). On a more local scale, this arc activity produced the Oligocene to earliest Miocene belt of intrusions, calderas, and related mineral deposits comprising much of the Pioche-Marysvale mineral belt. In general terms, this magmatic activity is of the calc-alkalic (to high-K calc-alkalic) magma series (Westra and Keith, 1981).

Comparison of the O.K. Mine with Porphyry Copper Deposits

Numerous similarities exist between the O.K. deposit and porphyry copper deposits. In terms of tectonic setting, the O.K. deposit conforms to porphyry copper models in that it lies within a presumably subduction-related calc-alkalic magmatic arc. Porphyry copper mineralization of the same general age and setting as the O.K. deposit includes the Bingham Canyon (39-36 Ma) and Silver City stock (31 Ma) near the Tintic district.

Metal contents of porphyry copper deposits may range from molybdenum poor to molybdenum rich. A continuum between molybdenum-rich porphyry copper deposits and molybdenum-rich calc-alkalic stockwork molybdenum deposits was pointed out by Westra and Keith (1981). Westra

and Keith (1981) also note that high molybdenum concentrations in some porphyry copper deposits are typically associated with late magmatic differentiates, as may be the case of the aplite dike at the O.K. deposit. Minor precious metal values may also be associated with porphyry copper deposits. Thus, in terms of metal content, the O.K. deposit conforms to both porphyry copper and calc-alkalic stockwork molybdenum deposit models. No trace element data are available for the O.K. deposit.

Another similarity between the O.K. deposit and porphyry copper deposits is the general similarity of temperature and salinities of magmatic-hydrothermal fluids. Values determined for primary fluid inclusions at the O.K. Mine lie within the range documented for porphyry copper deposits of southwestern North America (Tittley and Beane, 1981).

Several important differences, however, exist between the O.K. Mine and porphyry copper deposits. Most striking is the difference in size. The O.K. deposit, and associated alteration zones (excluding the propylitic fringe), measures about 600 feet (183 m) in diameter. Typically, porphyry copper deposits are larger by a factor of 10 (Lowell and Guilbert, 1970).

Another important difference is the alteration and mineralization at the O.K. deposit. In porphyry copper deposit models, cooling of the host intrusive and attendant expulsion of an aqueous phase is responsible for generating the earlier altering and mineralizing fluids. Thus, initially at least, altering solutions are intimately related to the host intrusive. At the O.K. Mine, however, the host quartz monzonite appears to have been a passive host upon which the alteration and mineralization was superimposed.

Three aspects of hydrothermal alteration at the O.K. Mine differ significantly from porphyry copper deposits, including the lack of a potassic zone, presence of a silicic zone, and the lack of pyrite in the phyllic zone. Potassic alteration (characterized by secondary K-feldspar and/or biotite) was either never developed or was destroyed by later phyllic (quartz-sericite) alteration at the O.K. Mine. The destruction of earlier potassic alteration in porphyry copper deposits by the inward migrating phyllic assemblage is believed to be accompanied by the alteration of chalcopyrite to pyrite (Tittley and Beane, 1981). Complete absence of potassic alteration and the near absence of pyrite in the phyllic zone suggest that potassic alteration was never developed at the O.K. Mine.

Pyrite is a ubiquitous component (up to 10 percent) of phyllic alteration in porphyry copper deposits. Pyrite formation is generally attributed to the sulfurization of Fe extracted from biotite and is spatially associated with biotite (Beane, 1982). At the O.K. deposit, however, magnetite is intimately associated with biotite. Quantitative electron microprobe data, tabulated in table 2, shows that biotite associated with magnetite has a significantly lower FeO:MgO ratio than isolated biotite grains. This suggests that magnetite was at least partially formed from the Fe content of associated biotite. The preferential formation of magnetite instead of pyrite at the O.K. Mine probably reflects the relatively higher O_2 and lower S_2 fugacities during alteration.

A central silicic zone of alteration is not characteristic of porphyry copper deposits. Breccia pipes associated with

Table 2. FeO and MgO values of biotite grains in sample R-8.6B. The biotite that is spatially associated with magnetite has a significantly lower FeO:MgO ratio suggesting than the magnetite extracted from the biotite as it formed.

Biotite Spatially Associated With Magnetite	Biotite Not Associated With Magnetite	FeO	MgO	FeO/MgO
X		17.16	14.68	1.17
X		16.68	14.86	1.12
X		17.20	15.45	1.11
X		16.69	14.91	1.12
	X	18.34	13.64	1.34
	X	18.10	12.54	1.44
	X	17.66	14.59	1.21
	X	18.75	13.21	1.42

porphyry copper deposits may, however, have a higher quartz content.

Comparison of the O.K. Mine with Stockwork Molybdenum Deposits

Genetic models and classification schemes have recently been developed for stockwork molybdenum deposits (Mutschler and others, 1981; Westra and Keith, 1981). According to this work, deposits can be divided into two very distinctive sets, calc-alkalic (also known as low-fluorine or granodiorite molybdenite systems) and climax-type (also known as alkalic-calcic to alkalic molybdenum stockwork or high-fluorine or granite molybdenite systems) deposits. Comparisons of each of these with the O.K. deposit will be made.

Calc-alkalic stockwork molybdenum deposits—As mentioned above, these deposits are similar to porphyry copper deposits. In fact, it has been suggested (Westra and

Keith, 1981) that these deposits are gradational with porphyry copper deposits. For this reason, all similarities and differences between the O.K. Mine and porphyry copper deposits discussed above also apply to this deposit type.

Climax-type molybdenum deposits—Deposits of this type are characterized by strong enrichment of a lithophile element suite including F, Be, Sn, Li, Mo, W, U, and others. Alteration assemblages are zoned outwards from a central silicic zone (coincident with the molybdenum ore shell), through potassic, quartz-sericite, and argillic zones. Mineralization is typically formed at the apex of cupolas above silicic batholiths.

One deposit of this type, the Pine Grove deposit, is known in Utah. The Pine Grove deposit consists of disseminated molybdenum-tungsten mineralization hosted by the 24 Ma Pine Grove pluton and is located approximately 30 miles (48 km) west-southwest of the O.K. Mine. No intrusive rocks of the composition associated with climax-type deposits exist near the O.K. Mine. This, coupled with the apparent absence of fluorite in the O.K. deposit, would seem to rule out the possibility of climax-type mineralization at depth.

Comparison of the O.K. Mine with magmatic-hydrothermal breccia pipe deposits

Breccia bodies have long been recognized as a common feature of porphyry systems, occurring both in mineralized and barren systems. Sillitoe (1985) has recently devised a classification scheme for ore-related breccias and work by Burnham (1979, 1985) provides a genetic model for breccia formation. Magmatic-hydrothermal breccias have been divided into two types: pipes related to intrusions (unmineralized intrusive rocks) and breccias within porphyry-type ore deposits (Sillitoe, 1985). Since the O.K. Mine, as presently understood, cannot be considered a porphyry copper deposit, only the first of these breccia deposit types will be discussed. It should be noted that, in the absence of conclusive evidence, mineralized breccia pipes which appear to be unrelated to porphyry mineralization may, in fact, represent high-level manifestations of porphyry systems. The following description is summarized from Sillitoe (1985).

Magmatic-hydrothermal breccia pipes may occur individually or in clusters and are commonly located in the upper parts of, immediately above, or marginal to plutons or stocks. Pipes are generally circular to oval in cross section with a marked vertical elongation. Sizes and shapes of breccia fragments vary widely. Breccia fragments may be surrounded by variable proportions of rock flour, void space, or hydrothermal cement. Pre-existing structures may or may not control the localization of pipes.

Breccia pipes commonly contain copper mineralization. Molybdenum, tungsten and/or gold may also be economically important. Alteration is very common, especially in mineralized pipes, and consists of replacement and open-space-filling. Sericitization (accompanied by tourmaline) is the most common alteration type with chloritization, silicification, propylitic and K-silicate assemblages being less common. Alteration may either end abruptly at the edge of the pipe or extend up to tens of meters into the host rock. Replacement alteration, followed by open-space filling by gangue and ore

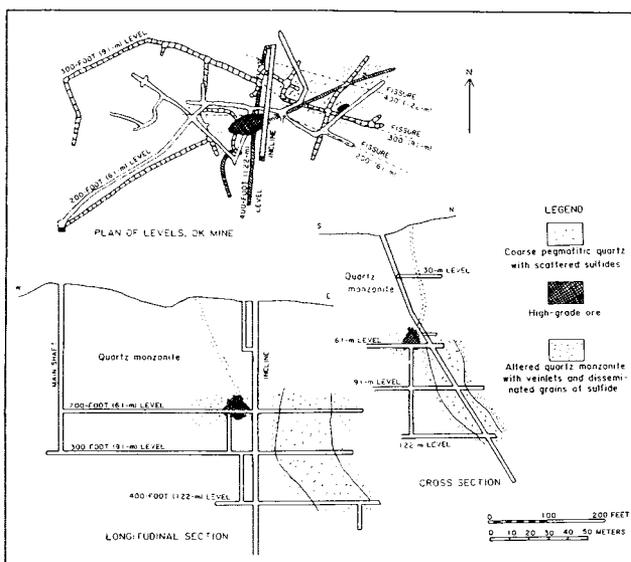


Figure 5. Plan and sections of the O.K. Mine.

minerals, commonly results in coarse-grained, well crystallized, pegmatitic textures. Mineralization is often restricted or of highest grade along the margins of the pipe. Fluid inclusion studies indicate that mineralizing fluids ranged in temperature from 310 to 470°C and in salinity from 1 to 50 equivalent weight percent NaCl.

Although not stated by previous authors, the silicic core at the O.K. Mine may be interpreted to represent a highly silicified breccia pipe. This interpretation is supported by descriptions of brecciation by Butler (1913), Steven and Morris (1904), Morris (1985), and this study, and by the close similarity between the O.K. Mine and the breccia pipe deposit description outlined in the previous two paragraphs. The breccia pipe interpretation has apparently been debated by industry geologists with no clear consensus.

Similarities between the breccia pipe deposit description and the O.K. Mine include size, morphology, mineralization characteristics, host rock, geologic setting, alteration, presence of tourmaline, temperature and salinities of hydrothermal solutions, and coarse texture of gangue minerals. Differences occur only in the degree of hydrothermal alteration. The degree of silicification of the pipe and the extent of wall rock alteration around the pipe appear to be greater than is typical for ore-related breccia pipes.

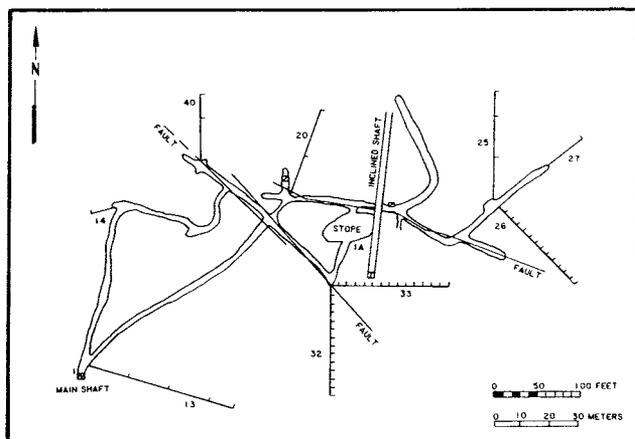


Figure 6. Map of the underground workings at the 200-foot (61-m) level of the O.K. Mine showing sample locations (1 and 1A) and faults.

CONCLUSIONS

Mineralization at the O.K. Mine is tentatively interpreted to be of the breccia pipe-type as described by Sillitoe (1985). Whether or not the pipe is associated with a porphyry Cu-Mo deposit remains to be determined; however, exploration has evidently not resulted in the discovery of such a deposit. It is unknown whether an unexposed intrusion at depth is responsible for pipe formation or if the pipe was formed by fluids expelled from the O.K. stock. Sillitoe (1985) and Burnham (1985) mention an example of a lensoidal quartz mass overlying the apex of a granite cupola at Panasqueira, Portugal (Kelly and Rye, 1979), a feature which may pertain to

the O.K. deposit. Burnham (1985) and Sillitoe (1985) outline a model for ore-bearing breccia pipe formation which may apply to the O.K. deposit. The reader is referred to these papers for further details.

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APPENDIX

Major element analyses of drill cuttings from the 200 foot (61 m) level of the O.K. Mine.

For index map of the sample locations, see Figure 6. The first number of the sample location is the number of the horizontal drill hole form which the sample was taken. The second number is the footage along the hole.

The elements are listed as weight-percent oxide. "LOI" is the Loss On Ignition. This is the loss in weight of the sample on fusion into a glass bead. It is predominantly H₂O with minor amounts of Na, S, and CO₂.

OXIDE

SAMPLE IDENTIFICATION

	33-5	33-10	33-20	33-30	33-40	33-50	33-60	33-70	33-80	33-90	33-100	33-110	33-120	33-130	33-140
SiO ₂	69.47	67.57	66.06	68.34	65.66	65.54	65.06	64.18	65.13	68.09	67.08	64.10	66.70	65.04	63.97
Al ₂ O ₃	14.17	15.29	14.91	15.18	15.50	15.05	15.33	15.48	15.35	14.80	14.61	15.20	14.75	15.27	14.75
Fe ₂ O ₃	3.41	3.51	4.52	3.90	3.75	4.21	3.72	4.11	4.22	3.48	3.27	3.38	3.87	3.72	5.16
MgO	1.06	1.48	1.49	1.40	1.44	1.39	1.27	1.26	1.31	1.21	1.13	1.26	1.49	1.32	1.32
K ₂ O	4.88	5.02	4.89	4.62	4.39	4.68	4.46	4.23	4.16	5.35	4.58	4.29	4.03	4.15	4.02
Na ₂ O	1.73	2.54	2.02	2.22	2.74	2.11	3.21	2.88	2.64	1.69	2.38	2.27	1.80	2.88	2.83
CaO	.42	.46	.40	.51	1.48	.73	2.51	2.44	2.14	1.73	1.75	2.82	1.47	2.26	2.65
TiO ₂	.48	.48	.44	.44	.63	.58	.66	.64	.65	.60	.46	.46	.54	.52	.52
P ₂ O ₅	.15	.14	.15	.14	.15	.14	.15	.16	.15	.15	.14	.13	.16	.18	.18
MnO	.03	.03	.03	.03	.03	.02	.06	.04	.04	.02	.04	.04	.02	.04	.04
Cu	.56	.30	.96	.17	.28	.31	.16	.05	.13	.47	.27	.09	.12	.17	.17
LOI	3.96	3.64	3.50	3.51	3.74	3.53	3.52	3.69	3.19	3.18	3.03	3.13	3.22	3.40	3.40
TOTAL	100.32	100.46	99.37	100.46	99.79	98.29	100.11	99.16	99.11	100.77	98.74	97.17	98.17	98.15	99.01

OXIDE

SAMPLE IDENTIFICATION

	32-5	32-10	32-20	32-30	32-40	32-50	32-60	32-70	32-80	32-90	32-100	32-110	32-120	32-130	27-5	27-50
SiO ₂	65.74	65.86	64.22	65.47	64.68	64.81	64.59	64.14	66.83	64.76	64.20	63.82	63.20	63.81	64.04	63.78
Al ₂ O ₃	15.44	15.29	14.48	15.41	15.32	15.82	15.69	15.53	15.20	15.40	15.56	15.45	15.26	15.32	15.66	15.69
Fe ₂ O ₃	3.60	4.12	6.00	4.66	4.23	3.74	4.05	4.40	3.18	3.95	4.30	4.36	5.97	5.29	4.12	4.32
MgO	1.54	1.54	1.36	1.54	1.37	1.31	1.41	1.46	1.33	1.41	1.53	1.85	1.72	1.64	1.50	1.38
K ₂ O	4.74	4.63	4.04	4.06	4.01	4.01	4.01	4.14	5.09	3.92	3.95	3.67	3.53	3.66	3.91	4.04
Na ₂ O	2.81	2.72	2.57	2.66	2.98	2.94	3.33	3.17	2.89	3.36	3.11	3.18	3.26	3.30	3.08	3.16
CaO	.60	.78	1.13	1.47	2.22	2.39	2.85	2.16	1.15	2.33	2.94	3.34	3.55	3.47	2.95	2.96
TiO ₂	.50	.51	.46	.54	.53	.48	.50	.53	.48	.56	.57	.61	.58	.59	.52	.50
P ₂ O ₅	.16	.17	.16	.17	.13	.12	.21	.16	.16	.17	.22	.18	.20	.18	.15	.13
MnO	.02	.05	.02	.04	.03	.04	.05	.04	.04	.06	.04	.04	.05	.05	.03	.03
Cu	.10	.08	1.39	.09	.11	.11	.07	.10	.37	.24	.23	.12	.12	.10	.09	.08
LOI	3.98	3.62	3.64	3.68	3.57	3.40	2.94	2.91	2.60	2.14	2.43	2.46	2.49	2.32	3.82	3.28
TOTAL	99.23	99.37	99.47	99.79	99.18	99.17	99.70	98.74	99.32	98.57	99.08	99.08	99.93	99.73	99.87	99.35

OXIDE

SAMPLE IDENTIFICATION

	26-5	26-10	26-20	26-30	26-40	26-50	26-60	26-70	26-80	26-90
SiO ₂	72.09	66.95	65.12	65.94	67.06	65.60	64.50	65.25	67.11	64.28
Al ₂ O ₃	13.35	15.13	15.66	15.11	14.89	15.20	14.97	14.96	14.83	14.66
Fe ₂ O ₃	1.11	1.86	2.90	3.64	3.91	3.79	4.43	3.62	3.69	3.40
MgO	.26	.46	.85	1.36	1.42	1.42	1.46	1.26	1.39	1.37
K ₂ O	7.39	9.21	8.58	5.25	4.81	4.69	4.97	4.81	4.52	4.70
Na ₂ O	.80	.56	1.18	1.95	2.36	2.44	2.18	2.19	1.92	1.94
CaO	.08	.15	.33	1.64	1.10	1.02	.80	1.39	.57	1.57
TiO ₂	.60	.55	.56	.52	.73	.50	.72	.49	.47	.57
P ₂ O ₅	.10	.12	.18	.14	.14	.14	.15	.14	.15	.15
MnO	.05	.07	.06	.03	.04	.06	.03	.02	.02	.04
Cu	.07	.51	.66	.15	.15	.09	.30	.09	.07	.08
LOI	4.39	4.48	3.92	3.28	3.08	3.17	3.56	3.88	3.78	4.67
TOTAL	100.29	100.05	100.00	99.01	99.69	98.12	98.07	98.10	98.52	97.43

OXIDE

SAMPLE IDENTIFICATION

	26-100	26-110	26-120	26-130	25-5	25-50	25-100	25-130
SiO ₂	65.15	64.33	65.07	65.70	68.69	66.63	64.74	63.60
Al ₂ O ₃	14.56	14.93	14.81	14.78	14.74	14.63	15.30	15.10
Fe ₂ O ₃	3.54	3.33	3.44	3.39	2.29	2.91	4.70	4.72
MgO	1.48	1.34	1.49	1.42	.79	.73	1.26	1.25
K ₂ O	3.84	4.53	4.99	5.11	7.47	6.45	4.39	4.62
Na ₂ O	1.24	2.38	2.32	1.84	.52	.91	3.13	2.92
CaO	2.90	1.30	1.44	2.36	.33	.30	1.79	1.99
TiO ₂	.56	.51	.52	.47	.61	.55	.50	.49
P ₂ O ₅	.17	.14	.14	.13	.17	.13	.14	.15
MnO	.03	.03	.03	.06	.02	.01	.02	.03
Cu	.09	----	----	.09	.74	.86	.05	.12
LOI	4.53	4.38	3.88	4.02	4.23	3.98	3.43	3.03
TOTAL	98.09	97.20	98.13	99.37	100.60	98.09	99.45	98.02

OXIDE

SAMPLE IDENTIFICATION

	40-10	40-50	20-5	20-50	20-110	14-50	14-30	13-5	13-50	13-100	13-150	13-180	R-9.1	R-8.8B	OC-4	OC-9
SiO ₂	69.98	68.34	67.92	66.27	66.74	64.38	64.93	63.66	62.54	63.51	63.02	63.23	71.40	67.56	67.61	66.18
Al ₂ O ₃	13.93	15.36	14.53	14.60	15.36	15.39	15.69	15.77	15.49	15.77	15.43	15.42	13.03	14.71	14.67	14.75
Fe ₂ O ₃	2.01	3.36	2.56	3.88	4.41	4.67	4.99	4.63	4.77	5.25	5.25	5.26	2.29	4.48	4.05	3.98
MgO	.98	1.23	.94	1.36	1.45	1.57	1.70	1.56	1.92	1.75	1.61	1.78	.81	1.50	1.13	1.35
K ₂ O	6.64	4.52	6.72	4.05	4.48	4.35	4.28	3.84	3.69	3.81	3.75	3.65	6.47	2.88	4.58	4.04
Na ₂ O	.76	2.54	.50	1.90	2.52	2.54	2.64	3.55	2.61	3.90	3.74	3.70	.29	2.07	3.02	3.39
CaO	.26	.96	.26	1.17	2.30	.75	.73	4.31	4.17	3.62	3.68	3.77	.22	.40	2.06	2.41
TiO ₂	.47	.48	.45	.53	.50	.59	.55	.36	.70	.51	.69	.72	.46	.61	.50	.56
P ₂ O ₅	.14	.14	.15	.15	.15	.17	.16	.20	.20	.19	.18	.18	.20	.19	.17	.19
MnO	.01	.02	.02	.03	.04	.03	.03	.04	.04	.04	.04	.04	.02	.01	.03	.03
Cu	.23	.18	.66	.23	.33	.72	.50	.06	.06	.13	.09	.06	---	---	---	---
LOI	3.83	3.39	4.18	3.97	3.19	2.93	2.83	1.85	1.87	1.42	1.65	1.78	4.21	4.06	1.64	1.75
TOTAL	99.24	100.53	98.99	98.14	101.47	98.09	99.03	99.83	98.06	99.90	99.13	99.59	99.40	98.47	99.46	98.63

