BULLETIN 53

Clastic Dikes Intruding Cretaceous Coals of Western Colorado

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Contents

FIGURES

Abstract

Clastic dikes are common in North American coals that accumulated in marginal-marine environments, and they are rare to absent in coals that accumulated in continental settings. Clastic dikes are widespread in western Colorado coal fields where they intrude many thick coal seams. They are particularly abundant in coals mined in the southern part of the Piceance Basin, the focus of this study, near the towns of Palisade and Somerset. Here, coal seams rest directly on or just above a thick shoreface sandstone bed that is underlain by a thick tongue of the Mancos Shale. Dikes are far less common in coals mined in the northeastern part of the Piceance Basin and in the southeastern part of the Green River Basin, near the town of Craig. There, most commercial coal seams being mined are hundreds of meters above the nearest thick shoreface sandstone that is underlain by a thick marine shale tongue. Clastic dikes within the Craig study area are discussed only briefly because of their limited numbers and poor documentation.

Three principal styles of clastic dikes have been recognized by origin: *fault-fill*, *channel-margin*, and *joint-sourced dikes*. Channel-margin and fault-fill dikes are relatively small and uncommon features that have little impact on coal production. *Joint-sourced dikes* are by far the most abundant type of injection feature and are further subdivided into four groups on the basis of their geometry: *pyramidal-*, *sigmoidal-*, *columnar-*, and *irregular-shaped dikes*. Dikes can exceed 3 m thick, extend hundreds of meters laterally, and commonly penetrate entire coal seams.

Joint-sourced dikes are believed to be controlled by extension and release fractures that formed in young, poorly consolidated floor and roof sediments that enclosed peat beds. Water, from the dewatering of the underlying Mancos Shale, was channeled through fractures in the poorly consolidated shoreface sand beneath the peat. Here, sand (and fine-grained material) was washed into suspension and carried to the base of peat beds where preferred avenues were established through the peat to low pressure sites in compacted roof sediments. Evidence that joint-sourced dikes are controlled by fractures in floor and (to a lesser degree) roof sediments, includes

1) the bimodal orientation of fractures in the coal floor rock that parallels the bimodal orientation of dikes,
2) a well-exposed dike that is physically connected to fractures in the underlying shoreface sandstone that are bound by fluid escape features,
3) dikes that are dominantly relatively straight and laterally extensive,
4) dikes that mostly penetrate both the floor and roof rock of coal seams,
5) sharply bound dikes in the roof rock that form jagged saw-tooth geometries strongly resembling filled fractures, and
6) dike material that is petrographically indistinguishable from that of the sandstone floor.

Examinations of thin sections, polished blocks of dike material, and selective dike exposures along mine ribs indicate that dike material migrated laterally (as well as vertically) early in the coalification process and at relatively shallow burial depths. Finely serrated dike contacts that penetrate between coal bands or lithotypes form millimeter-scale sills. Delicate coalified plant fibers that penetrate dike margins are mostly horizontal to subhorizontal, indicating that a highly fluid slurry of sand and water gradually migrated through the matted peat or soft brown coal. The presence of coarse, centimeter-scale sills that extend several meters from their attachment points at the margins of dikes show that injection exceeded lithostatic load. Overpressuring of shoreface sands, resulting from dewatering of

underlying marine shale, is believed to be the key factor in the formation of large scale dikes in marginal marine coal seams.

Clastic dikes are common features that occur in coal fields around the world. Within the Piceance Basin, they have increased production costs and have caused a wide range of mining problems that have resulted in mine closures. The purpose of this study is to provide mine operators and researchers with current information on the nature and composition of clastic dikes.

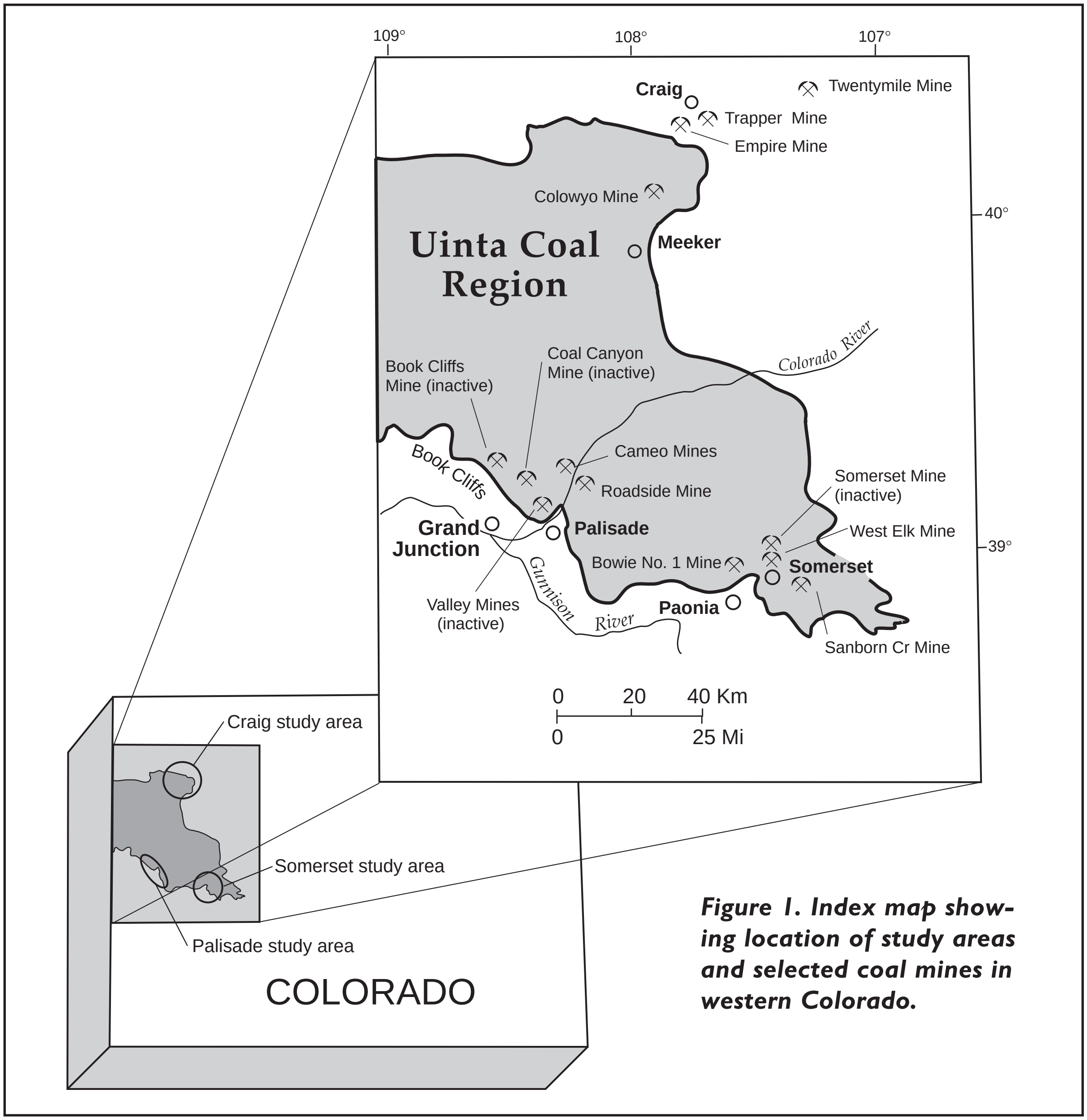


Figure 1. Index map showing location of study areas and selected coal mines in western Colorado.

Introduction

Clastic dikes are ubiquitous features that have been reported in coal fields around the world. As early as the late 1800s, clastic dikes were recognized as widespread features in North American coal fields. Crane (1898) reported, "there are few, if any, coal-mining localities known in the United States where dikes do not occur." The relative abundance of clastic dikes in coal beds, as compared to that of the adjacent strata, indicates that peat/coal beds are favorable hosts of clastic dikes. Newsom (1903) recognized this favorability in an early study and concluded, "it is not surprising that vegetable matter undergoing coalification should become highly intersected with clastic dikes." Later studies by Hardie (1991, 1992, 1994), Hardie and Bostick (1993), and Hardie and Fleck (1991) concluded that clastic dikes are particularly abundant in coals that accumulated in marginal-marine settings and that those sedimentary deposits that record the transition from marine to lower coastal plain settings favor the formation of dikes. In western Colorado (and most other areas of marginal-marine coals), the key factors in the formation of most dikes are the overpressuring of underlying shoreface sands resulting from dewatering of the underlying marine shale and the development of fracture joints.

Sandstone dikes are abundant in western Colorado coal fields (Figs. 4, 5, 6, 7, and 8). They range from small-scale features a few centimeters thick that extend a few tens of meters laterally, to large features that extend more than 2 km laterally and have thicknesses that challenge mining equipment. They have caused a wide variety of mine problems that significantly impact the economics of coal production and have resulted in mine closures. The purpose of this investigation is to provide western Colorado coal mine operators with information on the nature, mineralogy, geometry, and distribution of clastic dikes so they can most effectively manage coal production where coal seams are intersected by dikes. This project was funded through the Colorado Severance Tax Operational Fund as part of the Colorado Geological Survey's program to support economic geologic activities in Colorado.

The three study areas targeted in western Colorado: the **Palisade study area**, located north of the town of Palisade; the **Somerset study area**, near the towns of Somerset and Paonia; and the **Craig study area**, that includes the area adjacent to the town of Craig in the northeastern part of the Piceance Basin and in the southeastern part of the greater Green River Basin (Fig. 1). The Craig study area is discussed only briefly because dikes there are poorly documented, small, and relatively uncommon, and they have little impact on mining. However, as coal mining continues near Craig and production horizons move progressively lower in the stratigraphic section and requires underground mining methods, clastic dikes will likely be encountered. These three study areas were selected for the following reasons:

1) they are major coal producing areas of western Colorado,
2) clastic dikes are present, and

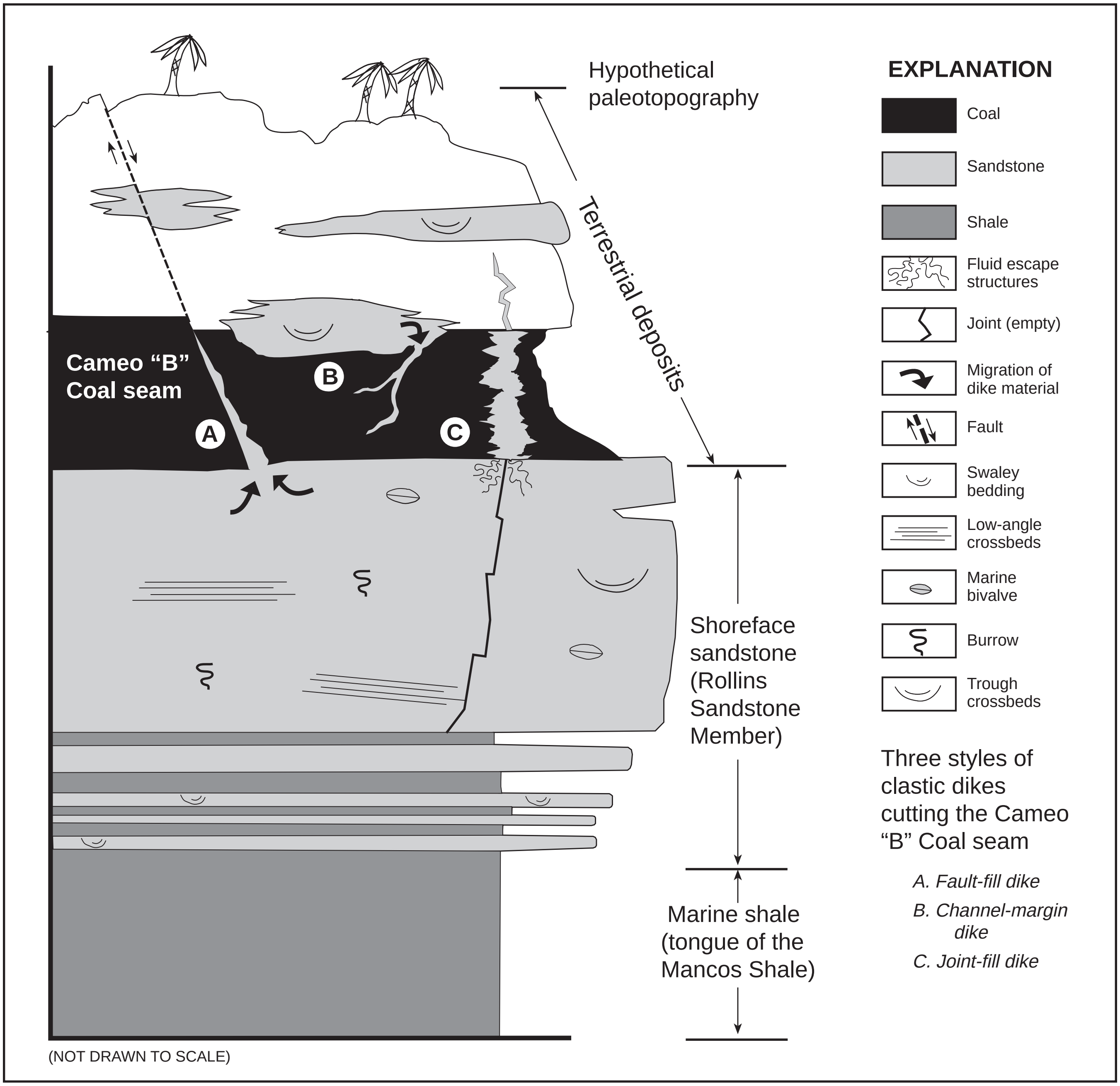


Figure 2. Diagrammatic section illustrating emplacement of three styles of clastic dikes in a coarsening upward regressive sequence in the Palisade and Somerset study areas.

3) many active and inactive coal mines provided opportunities to study dikes in three dimensional exposures along mine entries and crosscuts, and along the floors and high walls of strip pits.

Three principal styles of clastic dikes have been recognized by their mode of origin in western Colorado: *fault-fill*, *joint-sourced*, and *channel-margin dikes* (Fig. 2). Channel-margin dikes are small-scale siliciclastic injections that seldom penetrate deeper than the upper meter of a coal seam (Fig. 9). Commonly, they are attached to channel-sandstone bodies that make up the roof of coal seams. *Fault-fill dikes* are rare, high-angle, fault-bound, siliciclastic bodies that rarely exceed 1 m in thickness and can cut entire coal seams (Fig. 10). *Joint-sourced dikes,* the most abundant style of dike, are siliciclastic injections that

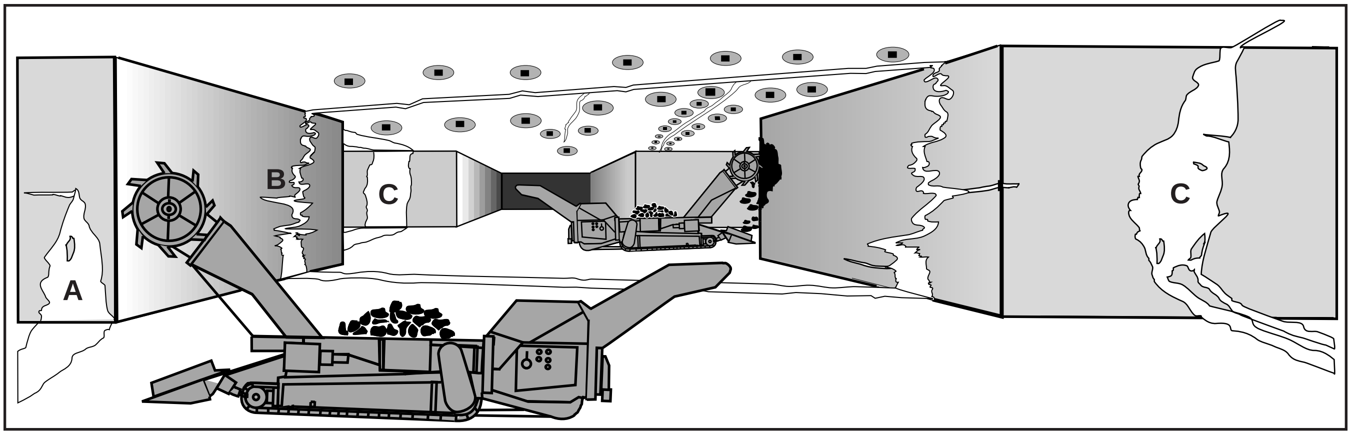


Figure 3. Sketch showing four geometries of joint-sourced dikes: A, pyramidal-, B, sigmoidal-, C, columnar-, and D, irregular-shaped dikes.

commonly penetrate entire coal seams (Fig. 3). They can exceed 3 m in thickness and extend more than 2 km laterally (Fig. 8). Fault-fill and channel-margin dikes are discussed in far less detail than joint-sourced dikes because they are small scale features that are not as well documented, less common, and have only minor impact on coal production. They are included in this report primarily to complete the theme on western Colorado clastic dikes.

Data were collected from outcrop studies, in-mine investigations, mine hazard maps, mine records, and personal communications with mine operators. In the Palisades study area, mine data were collected from the Book Cliffs, Roadside North, Roadside (south), Cameo, Cameo No. 1, and Coal Canyon Mines (Fig. 1). In the Somerset study area, data were compiled from the Somerset, Sanborn Creek, and West Elk Mines. In the Craig study area, data were gathered primarily from the Empire Mine. The Colowyo, Twentymile, and Trapper Mines played no significant role in this study because they produce coal from an interval hundreds of meters above the nearest thick, shoreface sandstone unit that is underlain by a thick marine shale—an interval where thick and laterally persistent dikes are rare to absent. Mine investigations were hampered by deteriorated mine workings and sealed-off areas that rendered many mined-out areas inaccessible. In accessable areas, coal cutting equipment commonly excavated 2 or more cm into the coal roof rock

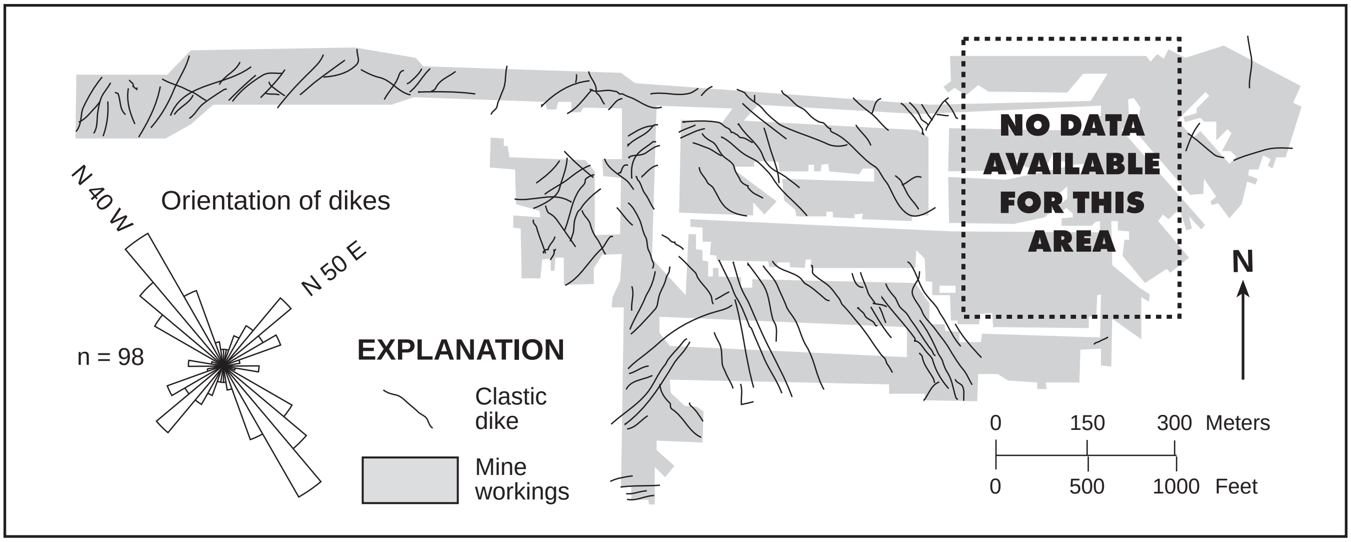


Figure 4. Distribution and orientation of principal clastic dikes in the Cameo Mine, Palisade study area.

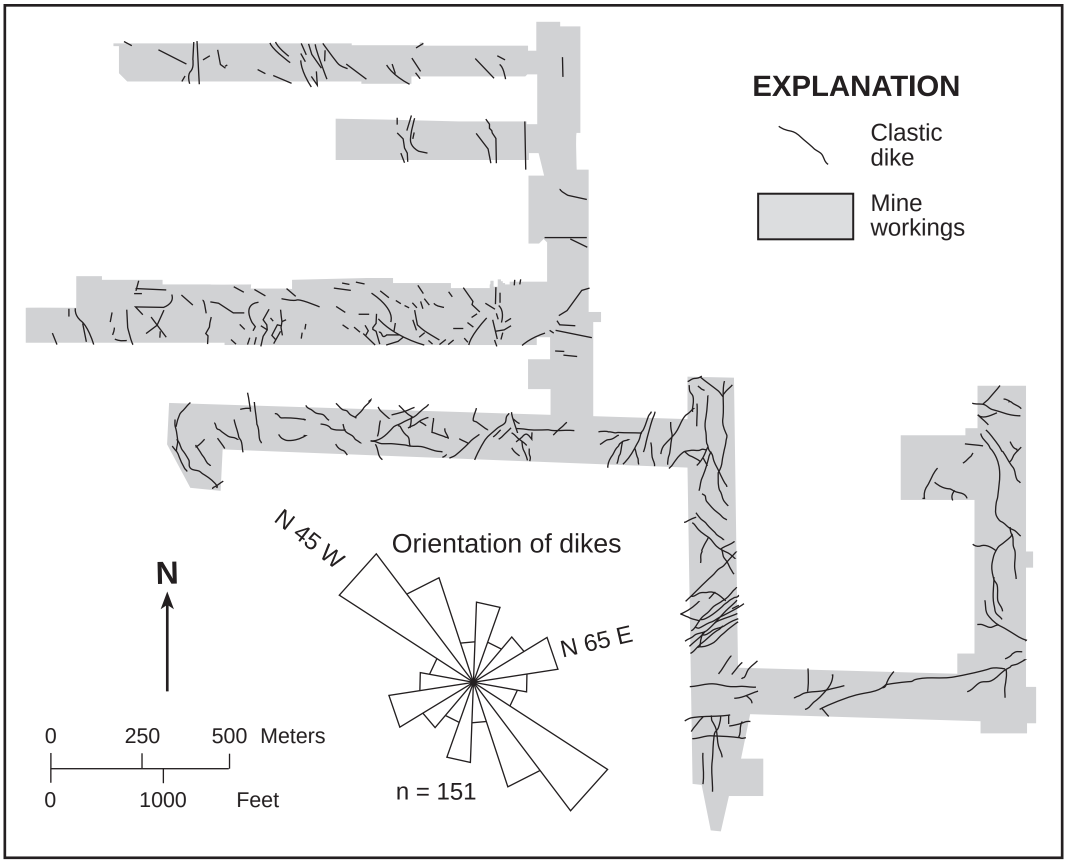


Figure 5. Distribution and orientation of principal clastic dikes in the Cameo No. 1 and Roadside North Mines, Palisade study area.

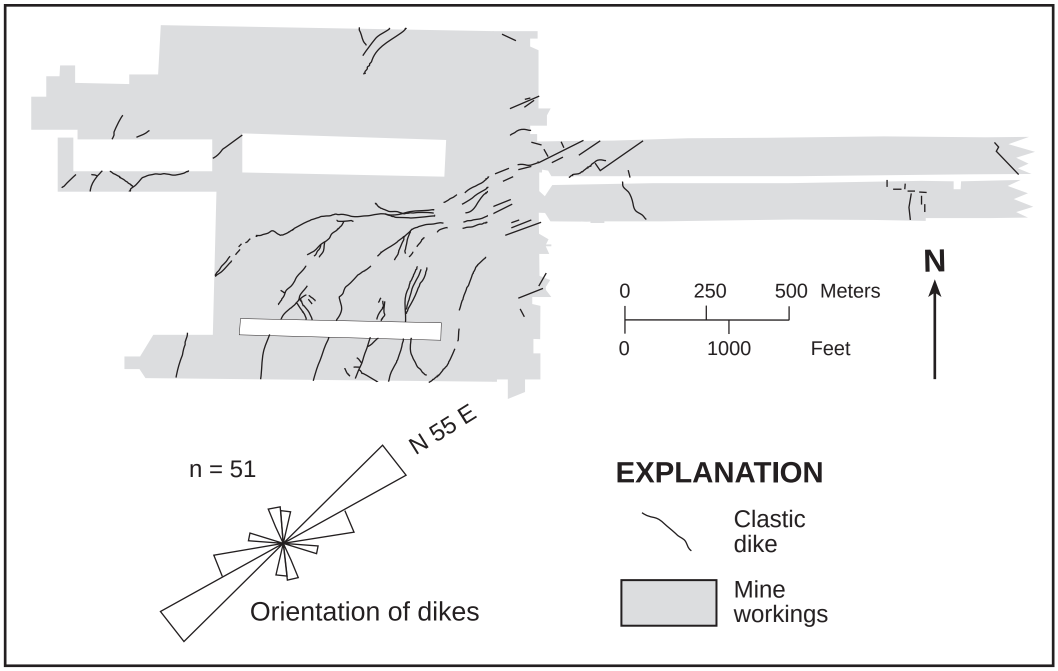


Figure 6. Distribution and orientation of principal dikes in the Roadside Mine, Palisade study area.

exposing dikes across the coal/roof interface. Dikes in coal floor rocks were studied along outcrops, along rare sections of exposed floor rocks in mine entries, and in the Coal Canyon strip pit floor. Rock samples were analyzed using X-ray diffraction, binocular, and petrographic examination. Quantitative results were determined by point counting 300 mineral grains per thin section. Dike distribution and trends were mostly derived from mine hazard maps provided by mine operators.

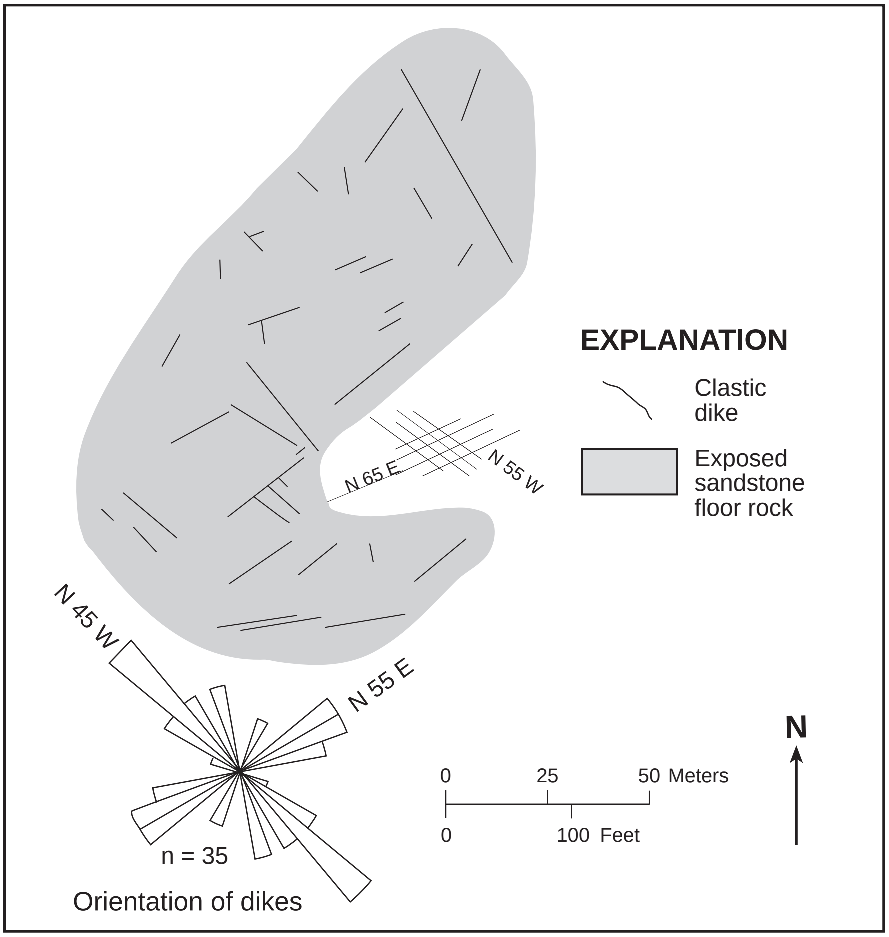
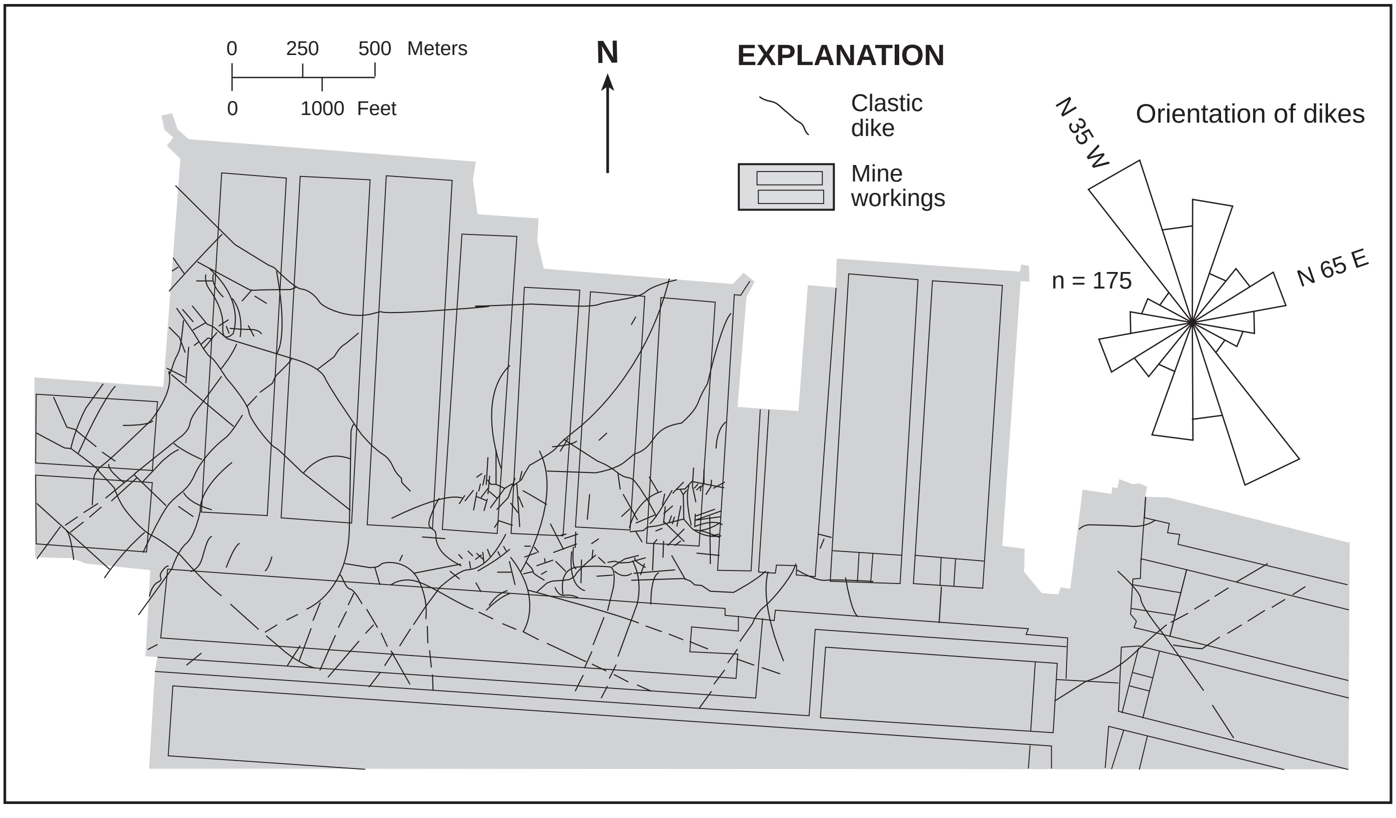


Figure 7. Orientation of dikes and joints in the Coal Canyon Mine strip pit, Palisade study area.

Figure 8. Distribution and orientation of principal dikes in the West Elk Mine, Somerset study area.



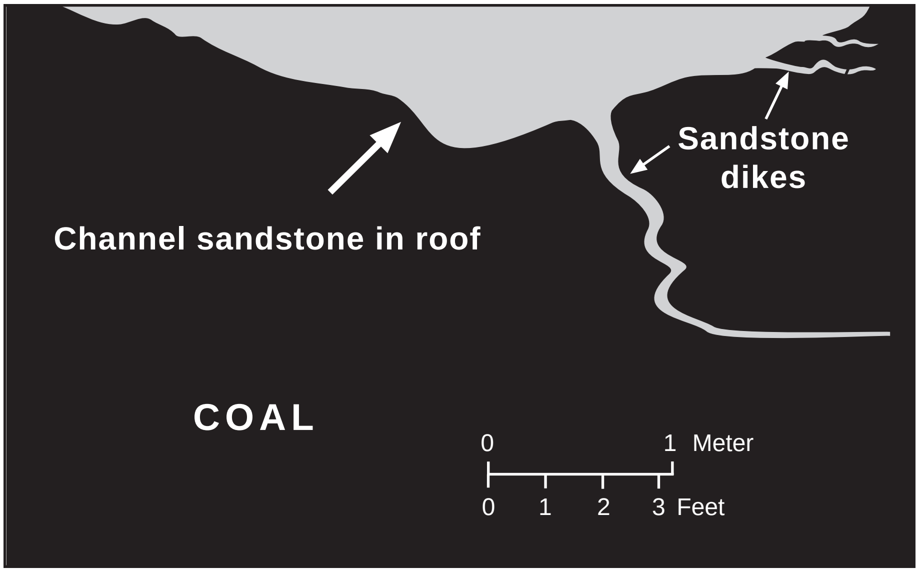


Figure 9. Sketch showing several channel-margin dikes physically attached to a channel sandstone body in the "B" seam roof of the Cameo Mine, Palisade study area.

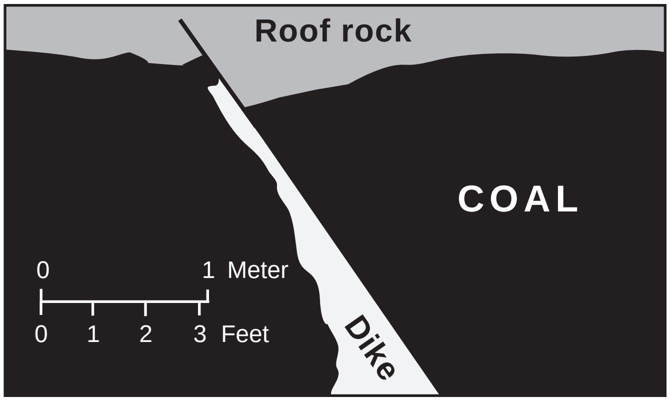


Figure 10. Sketch showing typical fault-fill dike from the "B" seam in the West Elk Mine, Somerset study area.

Depositional History

The Piceance Basin is a Laramide structural and depositional basin located along the northeastern edge of the Colorado Plateau in western Colorado (Fig. 1). Deep-water marine deposits of the Upper Cretaceous Mancos Shale are overlain by rocks of the Campanian age Mesaverde Group. The Mesaverde Group is an extensive regressive (Dunn, 1974) unit that exceeds 1,200 meters thick (Tweto and others, 1978) and records the southeastward progradation of the western shoreline of the epicontinental Cretaceous sea. The Mesaverde Group contains numerous deep water shale tongues that interfinger with transgressive/regressive marginal-marine rocks. These rocks are overlain by lower coastal plain strata to form a series of coarsening-upward sediment packages. The intertonguing of these sediments resulted from the southeastward progradation of shorelines that was interrupted by northwestward shoreline retreat during periods of relative sea-level rise (Spieker, 1949; Young, 1955; Weimer, 1960; Gunter, 1962; and Warner, 1964). Sediment packages contain a shoreface sandstone near the top that is overlain by continental deposits that commonly include thick coal or carbonaceous shale beds. Thick, progradational, shoreface sand bodies provided a favorable platform for the formation of peat deposits that accumulated in lower coastal plain settings immediately landward of shoreline systems. Stable high water tables, optimum subsidence, and the bypassing of coarse clastic sediments combined to form a favorable environment for the accumulation and preservation of peat (Tyler and McMurry, 1995). The lowermost coal seams that make up the more than 60 m thick Cameo coal zone, the focus of this study, is one such terrestrial deposit that persists throughout much of the Palisade and Somerset study areas. Following the withdrawal of the Cretaceous sea, marginal marine coal seams were buried by more than a thousand meters of Upper Cretaceous terrestrial strata (Tweto and others, 1978) and several thousand meters of Tertiary strata (MacLachlan, 1987).

Coal Geology and Stratigraphy

Principal coal production in the Palisade and Somerset study areas has been from the Cameo coal zone. Cameo coals are a low sulfur, bituminous rank coal of variable grade that extends across much of the southwestern Piceance Basin and are the principal producing horizons in the Somerset and Book Cliffs coal fields. Cameo coal is currently mined at the Roadside North, Roadside (south), Bowie No. 1, Sanborn Creek, and West Elk Mines; and prior to their closure, Cameo coals were mined at the Book Cliffs, Coal Canyon, Cameo No. 1, and Somerset Mines (Fig. 1). In the Palisade study area, minor coal production in the recent past has been from the underlying Palisade coal zone and the Anchor coal seam (Fig. 11). These three coal-producing horizons are highly intersected by clastic dikes. Coals at or near the base of the Cameo coal zone accumulated directly on and immediately above the Rollins Sandstone Member. The Rollins Sandstone is a thick, shoreface sandstone that is underlain by a thick, deep-water marine tongue of the Mancos Shale; the two units combine to form a coarsening upward sequence (Fig. 2). The stratigraphic framework and depositional setting of the Palisade coal zone and Anchor coal bed are similar to those of the Cameo coal zone in that they accumulated on or just above shoreface sandstone beds underlain by marine shale tongues. It should be noted that coal beds that comprise the Cameo coal zone, such as the "A" and "B" seams as well as the underlying Rollins Sandstone bed, are genetically equivalent but are believed to be stratigraphically higher (younger) in the Somerset area than in the Palisade study area because of the southeasterly, forward-stepping direction of the paleoshoreline (Fig. 11).

In the Craig study area, coal is produced from a number of horizons assigned to the Williams Fork Formation of the Mesaverde Group (Fig. 12). Discontinuous coal seams, some more than 6 m thick, are composed of high quality, low sulfur, subbituminous rank coal. The Williams Fork Formation consists of interfluvial and coastal plain sediments interrupted by thin marine sedimentary units; it rests directly on the Trout Creek Sandstone Member of the uppermost Iles Formation. Locally, the Iles Formation rests directly on a relatively thin tongue of the Mancos Shale and is roughly 30 m above the Loyd Sandstone Member of the Mancos Shale (Hardie and Zook, 1997). The author believes that the Loyd Sandstone is stratigraphically the highest shoreface sandstone underlain by a thick marine shale tongue (Fig. 12). Principal coals of the Iles Formation are assigned to the Black Diamond coal zone, which is stratigraphically just below the Trout Creek Sandstone. These coals are lenticular and rarely exceed a meter in thickness. The Twentymile, Colowyo, Trapper, Seneca II, and Empire Mines produce coal from horizons in the Williams Fork Formation that are more than 400 m above the Loyd Sandstone, the nearest shoreface sandstone underlain by a thick tongue of the Mancos. The Empire Mine, although temporarily inactive in 1997, produced coal from the "E" and

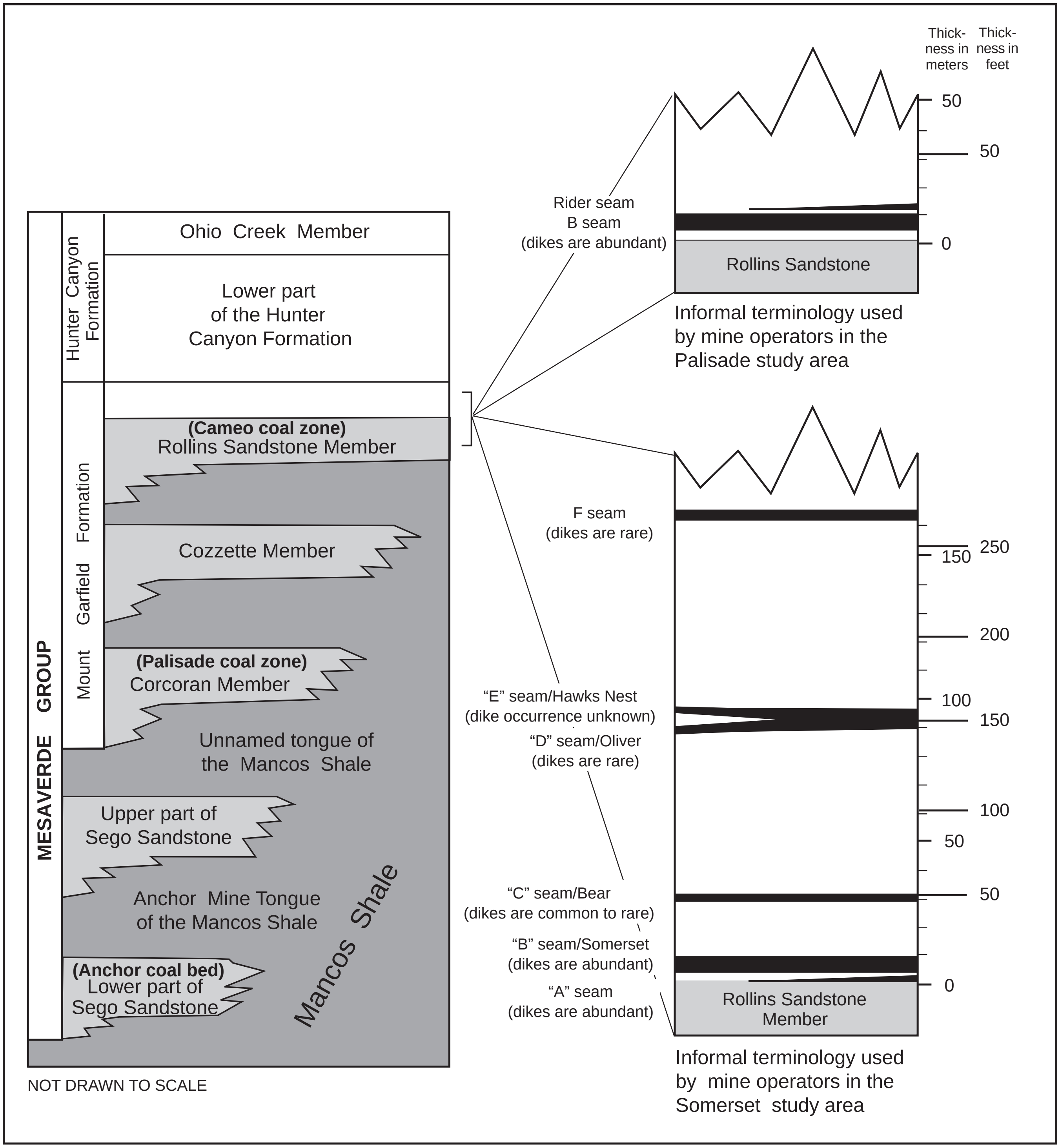


Figure 11. Generalized stratigraphic section showing stratigraphic terminology and informal coal seam names used in the Palisade and Somerset study areas.

"F" seams that are currently the lowest production coals, stratigraphically, in the study area (Fig. 12). The "E" and "F" seams are believed to be roughly equivalent to the Wadge seam and probably correspond to the coals of the upper Fairfield coal zone.

Mine operators in the Craig study area have reported only rare small-scale dikes except at the Empire Mine. Here, dikes are more common but still relatively rare and small as compared with those in the Palisade and Somerset study areas.

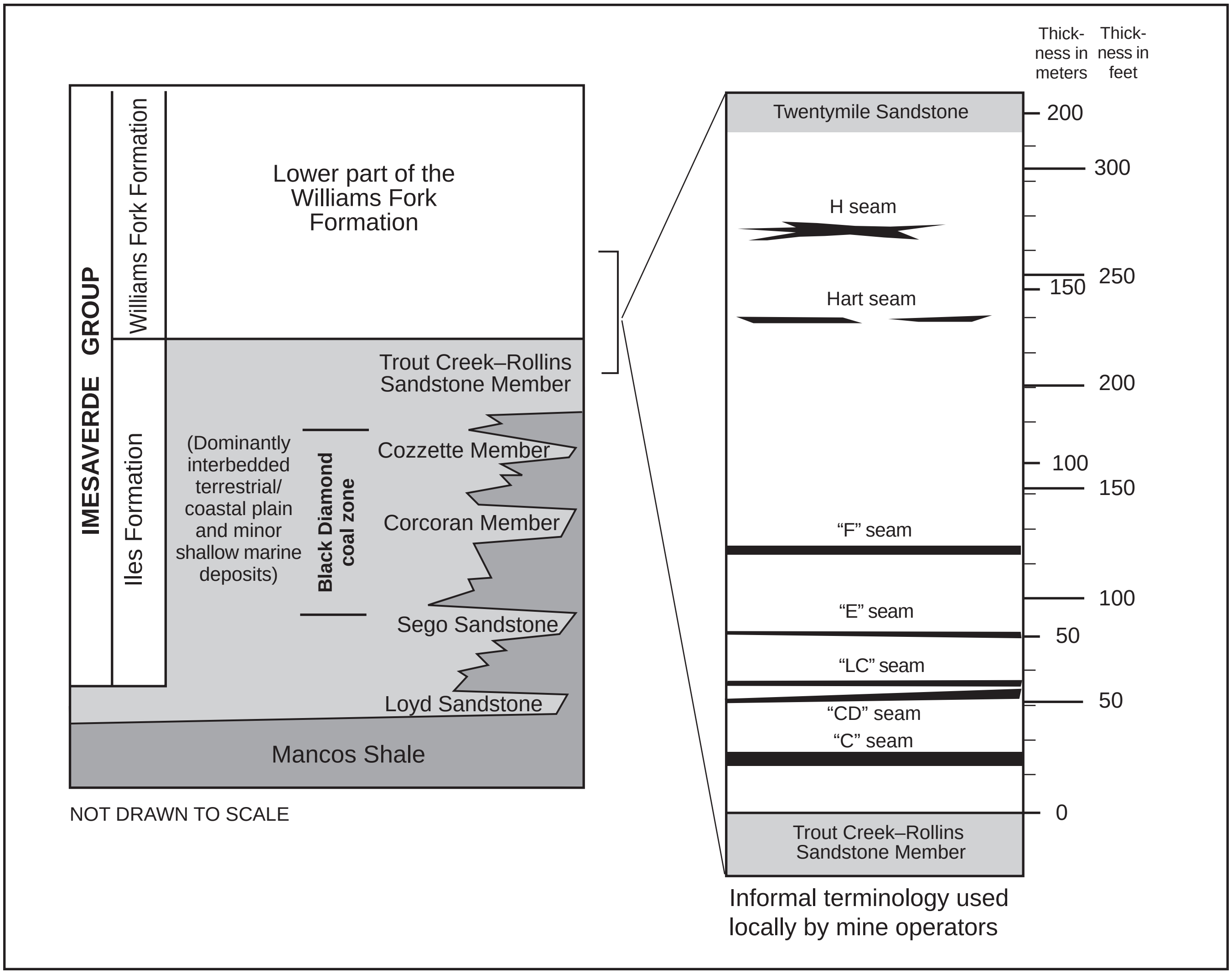
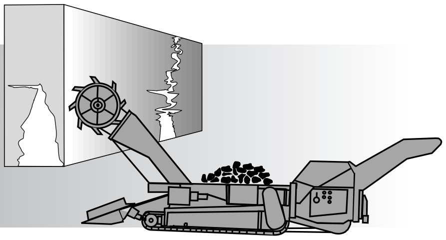


Figure 12. Generalized stratigraphic section showing stratigraphic terminology and informal coal seam names used in the Craig study area.

Previous Studies of Clastic Dikes in Western Colorado

Although clastic dikes have been observed in parts of the Piceance Basin since the late 1800s, little published work is available. Lake (1904) described a sandstone dike in the "Big Book Cliff Coal" seam (later renamed the Cameo coal zone) near the present day Roadside (south) Mine, he speculated that it formed when the coal was fractured and later infilled by sand and water from above. Erdmann (1934), in a broad study of the Book Cliffs Coal Field west of the town of Grand Junction, found that sandstone dikes were so numerous in the Cameo coal zone that they were a major descriptive characteristic. He proposed that the dikes were lithologically identical to the underlying Rollins Sandstone and suggested that the Rollins was their source rock. He made no attempt to determine their mode of origin. In the Craig study area, no published reports on clastic dikes are available. An overview of previous work on clastic dikes in North American coal fields is given by Damberger (1973). Recent unpublished mine studies on clastic dikes are either proprietary or otherwise not available.

Impact of Clastic Dikes on Mining

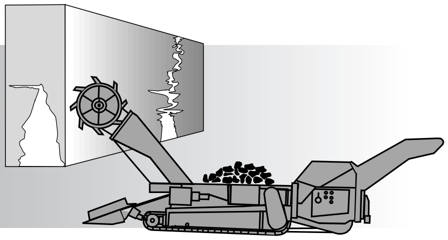


Dikes have caused a wide range of significant mine problems within the Piceance Basin including slowed production, unstable roof conditions, damage and increased wear of coal-cutting equipment, increased ash, infiltration of mine water or methane, and roof vibration when cut. They were a principal economic factor in the closure of the Cameo Mine (Dunrud, 1976) and Cameo No. 1 Mine (L. Rushke, oral commun., 1993). The Cameo Mine was reopened for limited production in 1996. In other coal fields across the U.S., dike-related mine problems, in addition to those mentioned above (Savage, 1910; Kerns, 1970; Simon and Hopkins, 1973; Dunrud, 1976; Doelling, 1979; Ellenberger, 1979; Johnson, 1982; Hill and Bauer, 1984; Moebs and Stateham, 1986; Chase and Ulery, 1987), include methane ignition from sparks generated by coal-cutting equipment (L. Adair, oral commun., 1991), increased methane emissions (Shea-Albin, 1993), and increased disposal handling of mine waste (Ellenberger, 1979). In the Appalachian Basin, high-angle clastic dikes that cut across each other form closed polygons or cells within coal seams. These cells contain pressurized methane gas that is suddenly released upon mining (Simon and Hopkins, 1973; McCulloch and others, 1975; Ellenberger, 1979; Jeran and Jansky, 1983). In mines where dikes trend parallel or subparallel to an entry or crosscut, they divide the roof into two segments that are unsupported by pillars creating a high potential for large-scale roof falls (Chase and Ulery, 1987). Clastic dikes have been a significant factor in mine closures (Boreck, 1986).

Classification of Dikes

In the three study areas, clastic dikes have been divided into three principal groups: *channel-margin dikes*, *fault-fill dikes*, and *joint-sourced dikes*. Dikes were assigned to a specific group primarily on the basis of their physical characteristics and interpreted mode of origin. *Channel-margin dikes* are scattered and relatively small-scale features that are physically attached to channel-sandstone bodies that make up the roof of coal seams (Fig. 9). *Fault-fill dikes* are high-angle, fault-bound features that are believed to have been injected along pre-existing fault planes (Fig. 10). *Joint-sourced dikes* display highly varied geometries and occur in conjunction with joint fractures in shoreface sediments. *Joint-sourced dikes* are subdivided, according to their geometry, into *sigmoidal-*, *pyramidal-*, *columnar-*, and *irregular-shaped dikes* (Fig. 3). Sills and pipes are classified separately as miscellaneous features because they are secondary injection features that formed from joint-sourced dikes. Sills are generally small-scale, concordant bodies that are attached to dikes. Pipes are isolated, centimeter-scale, ellipsoid-shaped bodies of dike material that can be seen in vertical exposures of coal along mine ribs and in outcrop.

Joint-sourced Dikes



DESCRIPTION

Joint-sourced dikes are by far the most abundant style of dike in the Palisade and Somerset study areas making up more than about 85 percent of all dikes examined. Joint-sourced dikes in the Craig study area are poorly documented and are believed to be rare; further reference to joint-sourced dikes in the following text is restricted to the Palisade and Somerset study areas. Dikes are particularly abundant in the Cameo coal zone but less numerous in the underlying Anchor and Palisade coal seams (Fig. 11). Dikes range from a few centimeters to more than 3 m thick and have been traced laterally more than 1,000 m along mine entries and cross cuts at the Somerset Mine (Dunrud, 1976) and more than 2,000 m at the West Elk Mine (Fig. 1). Dike material is mostly composed of light gray, dolomitic, well-indurated, fine-grained to very fine-grained, quartz sandstone. Some dikes are brightly stained by iron oxide suggesting that portions of these dikes are highly permeable. Iron-stained zones, which can extend across the entire width of dikes, are commonly composed of friable sandstone (Fig. 13). Dikes contain no recognizable sedimentary structure.

Dikes, when traced along the roof rock, can form unusual and complex networks. Dikes are commonly intersected at roughly 90° by numerous smaller, centimeter-scale dikes that are less than about 20 m in length. These smaller dikes range from relatively straight to jagged features that can abruptly split and coalesce (Figs. 14 and 15). In other mine locations, two or more dikes cut across other dikes at nearly right angles to form

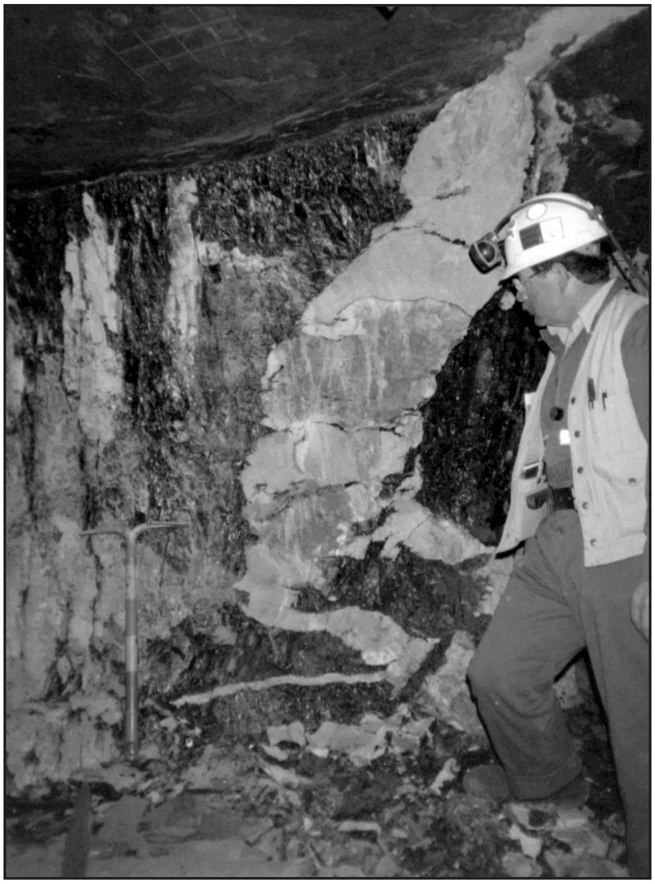


Figure 13. Photograph showing an irregular-shaped dike and sill in the Cameo Mine. Dark area in the central part of the dike is stained by iron oxide.

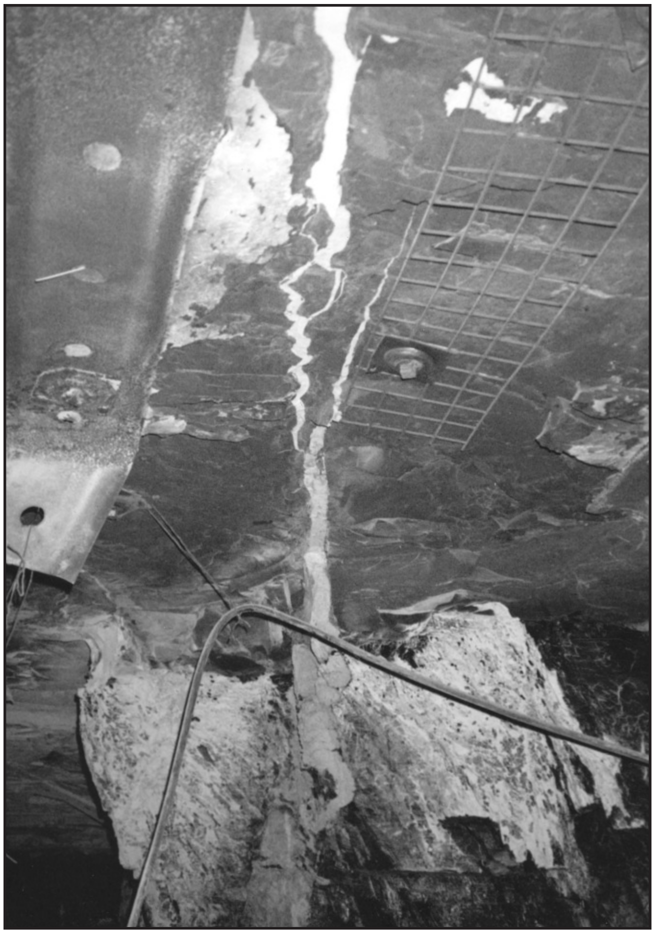


Figure 14. Photograph of dike material that formed a zig-zag pattern across the roof of the Cameo No.1 Mine and that resemble infilled fractures.

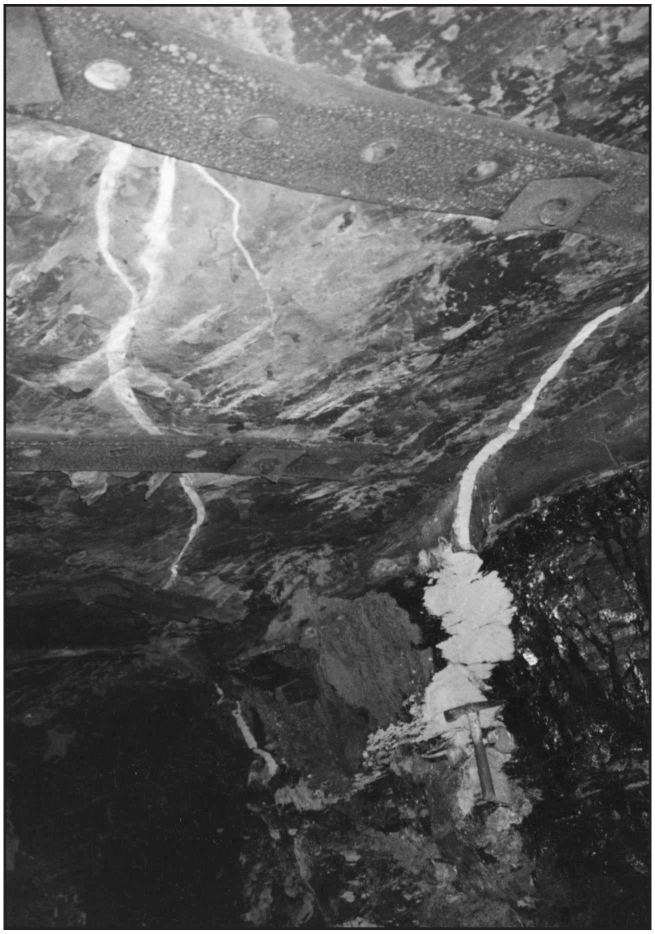


Figure 15. Photograph showing dike material that formed a splintered pattern across the roof of the Roadside (south) Mine and that resemble infilled fractures.

Figure 16. Photograph showing a cross-hatch pattern composed of small, intersecting dikes in the roof of the Cameo Mine and that resemble infilled fractures.

complex cross-hatch patterns like those shown in Figure 16.

Dike contacts are exceptionally sharp. Their appearance ranges from smooth, to undulate, to finely serrated, to jagged, or shredded. The character of the contacts appears to be partially controlled by the thickness and attitude of dikes. Thin, high-angle dikes are generally crenulated and have fair-

Figure 17. Photograph showing the smooth contacts and the discontinuous, crenulated character of a sigmoidal-shaped dike in the West Elk Mine.

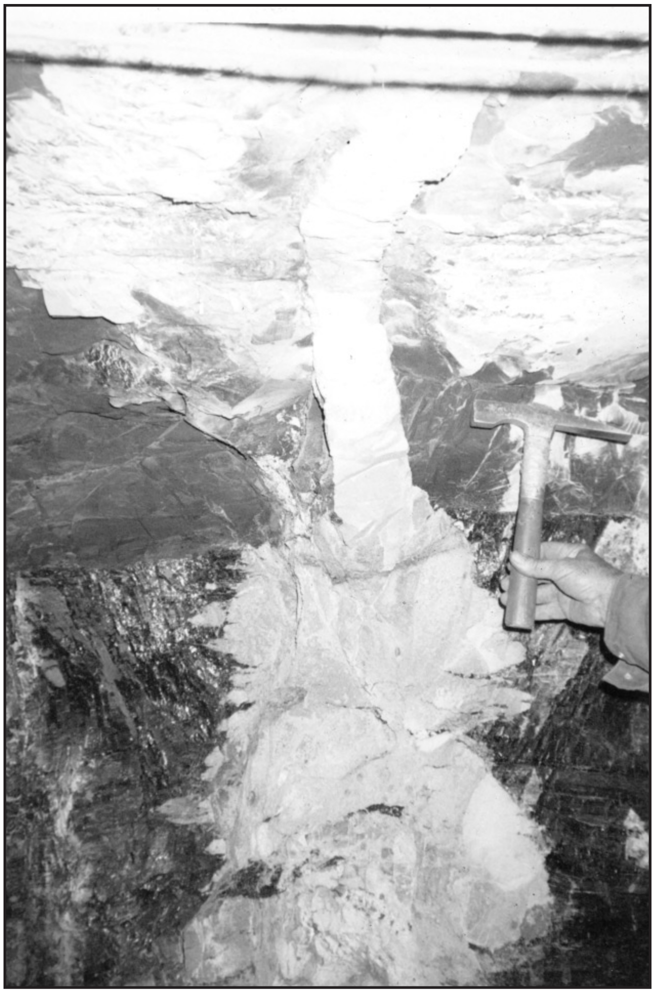


Figure 18. Photograph showing dike thinning at the roof line and jagged dike contacts at the Roadside (south) Mine.

ly smooth and undulate contacts (Fig. 17). Many of the curved segments of dike material are disjointed and display discontinuous contacts (Fig. 17). Contacts displayed by dikes that are more than about 0.4 m thick are commonly either finely serrated or jagged to shredded (Fig. 18). Finely serrated contacts are composed of hundreds of wedge-shaped millimeter- to centimeter-scale projections of dike material that interfinger with the layers of coal. Jagged to shredded contacts are composed of a series of crude, wedge-shaped projections as much as several centimeters thick that extend as much as 8 cm into the coal. Large- to medium-scale dikes that have relatively low penetration angles and those that exceed about 0.7 m thick are commonly bound by smooth to slightly undulate, slickensided contacts.

Dikes occur either as solitary features or in swarms and display very similar bimodal trends that correspond well to joints in the sandstone floor rock. Bimodal joint trends in the Coal Canyon strip pit floor, which is composed of the Rollins Sandstone and overlain by the Cameo "B" seam, measure N. 55° W. and N. 65° E. and are evenly spaced approximately 0.5 m apart (Fig. 7). Dikes that are exposed in unmined areas of the strip pit where the coal remains have very similar trends of approximately N. 45° W. and N. 55° E. Although most joints along the floor rock are open, some are filled with dike material that extends several centimeters above the surface of the floor rock. In the Cameo Mine, dikes are exceptionally long and straight and display trends of approximately N. 40° W. and N. 50° E. (Fig. 4).

Here, small-scale, intersecting dikes along the roof form cross hatch patterns that strongly resemble infilled fractures and have bimodal dike trends that are similar to those of bimodal joint trends in the nearby strip pit floor (Fig. 16). In the Cameo No. 1 and Roadside North Mines, similar dike trends of roughly N. 45° W. and N. 65° E. were measured (Fig. 5).

However, it is troublesome and inconsistent that dike trends measured in the nearby Roadside (south) Mine have a single dominant trend of roughly N. 55° E. that coincides with subordinate dike trends measured in the mines previously mentioned (Figs. 4, 5, and 7). Furthermore, the trends measured in the northwestern part of the Roadside (south) Mine display a curvilinear character that suggest that some unknown controlling factor, outside the scope of this study, locally influenced dike formation. Dike trends in the Somerset Mine (inactive) have a bimodal trend of roughly N. 75° E. and N. 45° W. In the West Elk Mine, near Somerset, the two dominant dike trends measure roughly N. 35° W. and N. 65° E. Although these trends are similar to those previously mentioned (except for the Roadside (south) Mine), the rose diagram in Figure 8 shows a great deal of scatter in trends that range between N. 65° E. and 0° N. It is believed that many of the smaller dikes that were included in the calculations of the rose diagram formed from the lateral migration of dike material and therefore had different controls than large-scale dikes. The lateral migration of dike material will be discussed later in the text.

Along a well-exposed outcrop near the abandoned Book Cliffs Mine, north of the town of Grand Junction, a joint-sourced dike is attached to joints in the Rollins Sandstone. Here, two joints that are roughly 0.8 m apart can be traced for tens of meters along the upper bounding surface of the Rollins Sandstone to the swollen base of a joint-sourced dike in the Cameo "B" seam. These joints are heavily stained with iron oxide. Within about one hundred meters of this dike, laterally extensive joints are bound on either side by convolute zones that are several centimeters wide and that display relief of a few centimeters above the adjacent bounding surface of the Rollins Sandstone (Fig. 19).

Coal cleat in the Cameo "B" seam has bimodal trends similar to those of joints and commonly can be traced cutting across small-scale dikes. The trend of coal cleat measures roughly N. 65° E. and N. 35° W. in the Palisade area, and roughly N. 70° E. and N. 50° W. in the Somerset area. There are no known examples where coal cleat is partially filled with sandstone dike material.

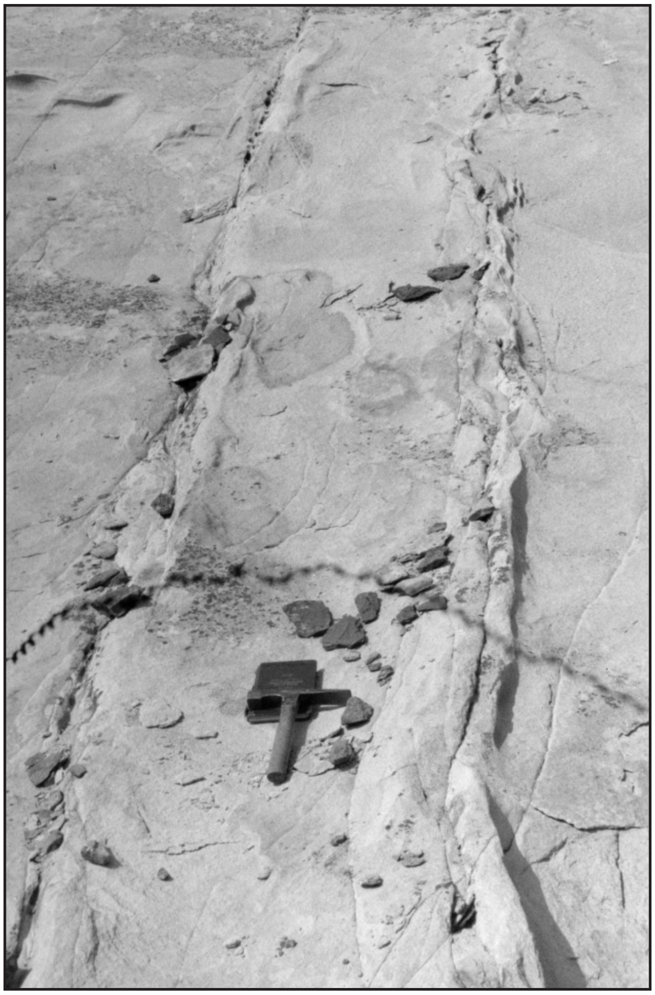


Figure 19. Photograph showing fluid escape features on either side of two fracture joints along the upper bounding surface of the Rollins Sandstone near the Book Cliffs Mine of the Palisade study area.

Dikes penetrate all or parts of coal seams at high angles that range from vertical to about 20° from vertical. Thick dikes, those greater than about 0.4 meters thick, generally penetrate the entire coal seam and into the roof rock. Smaller dikes are more likely either to pinch out at some distance below the coal roof line or to penetrate upward to the roof rock where they form convex-upward depressions (or inverted pressure points) along the coal and roof-rock contact (Fig. 20). At

Figure 20. Photograph showing a convex upward pressure point (slickensided) along the roof rock of the Roadside Mine that formed from the light colored dike material. Observe the dark-gray, millimeter-scale, claystone clasts in the dike material adjacent to the roof rock.

one well-exposed location in the Cameo No. 1 Mine where dike material rested against the lower surface of a convex-upward depression, well-rounded, millimeter-scale, claystone clasts were found scattered along a 5 cm thick interval immediately below the depression (Fig. 20). Clasts are composed of rock that was indistinguishable from that of the roof. In other areas, where dikes penetrate the roof rock, dikes abruptly thin to as little as a tenth of the thickness that they measured while in the underlying coal (Figs. 13 and 18). At a location in the West Elk Mine, very thin lamina in the siltstone roof rock were cleanly cut by a dike. The lamina were flat lying and undeformed against the dike contact.

COLUMNAR-SHAPED DIKES

Columnar-shaped dikes are common dike forms found in the Palisade and Somerset study areas. They generally penetrate entire coal seams at near-vertical angles and range from about 0.2 m to more than 3 m in thickness, although they rarely exceed 2.5 m thick (Figs. 3 and 21). They display relatively uniform thicknesses from floor to roof but can taper slightly towards the top of coal seams. Small dikes, those that are less than about 0.3 m thick, generally taper slightly and develop a mildly sigmoidal character near the roof suggesting that dike geometry is in part controlled by dike thickness. Columnar-shaped dikes are commonly found side by side with other forms of dikes and normally have the same penetration angle. Because they are thick and penetrate entire coal seams, they cause serious mine problems that include nearly the full range of problems discussed earlier under "Impact of Clastic Dikes on Mining."

PYRAMIDAL-SHAPED DIKES

Pyramidal-shaped dikes are fairly common dike forms that resemble crudely formed pyramids that are approximately vertical (Fig. 3). Such dikes are nearly always fault bound, measure from roughly 0.4 m to more than 2 m across at their base, and rapidly taper to a terminus in the middle to upper parts of coal seams (Figs. 22 and 23). However, at one location a thick pyramidal dike measuring 1.8 m across cut the entire coal seam and penetrated into the roof rock. At several other dike locations, small sills that measured a few centimeters thick extended horizontally from the terminus of the pyramidal dikes. Fig. 23 shows the terminus of a dike cutting a thin clastic sill about 1.5 m above the floor. Note that the fault trace shown in the figure parallels the dike margin and offsets the sill about 10 cm. The fine-grained sill material has filled that part of the fault trace between the two sills. Coarse-grained dike material has filled that part of the fault trace that lies between the sill and roof rock. Because of the extreme thickness of the base of pyramidal dikes combined with their general lack of complete penetration through coal seams, pyramidal dikes seldom cause roof problems but can cause serious damage to mine equipment, slow production, and create costly waste disposal

Figure 21. Photograph showing a columnar-shaped dike, more than a meter thick, in the Cameo No. 1 Mine. The rock hammer on the left side of dike is about 25 cm long.

problems. Where sills emanate from dikes, widespread rock contamination of the coal is typical.

SIGMOIDAL-SHAPED DIKES

Sigmoidal-shaped dikes are fairly common features that form crenulated, ribbon-like bodies that rarely exceed 20 cm in thickness and generally taper upward (Fig. 3). Dikes that are relatively thin and have attitudes that are roughly vertical, are highly crenulated and may or may not cut entire coal seams (Fig. 17). Those that are relatively thick, and(or) have lower angles of penetration, are less crenulated and can display broad folds that extend many tens of centimeters horizontally into the adjacent coal. Dikes that are relatively thick and roughly vertical are more likely to penetrate entire coal seams and cut into the roof rock. Sigmoidal-shaped dikes have little impact on mining because they are thin, easily cut by mine equipment, and commonly pinch out below the roof rock.

Figure 22. Photograph showing three dikes that penetrate part of the "B" seam in the Cameo Mine. Note the two sills emanating from the pyramidal-shaped dike on the right.

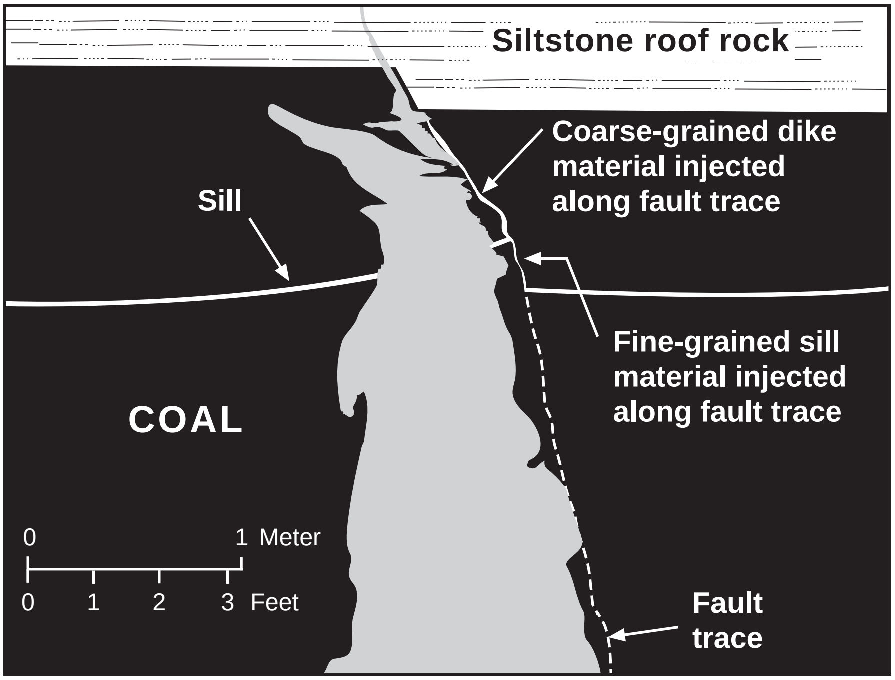


Figure 23. Sketch showing a pyramidal-shaped dike and a fault cut sill in the Cameo Mine. Following injection of the dike and sill, faulting occurred long the dike margin that was probably the result of differential compaction.

IRREGULAR-SHAPED DIKES

Irregular-shaped dikes are common and display unusual geometries when traced from floor to roof (Fig. 3). Not always is there a clear distinction between irregular-shaped dikes and other forms of joint-sourced dikes. Dikes range from roughly 0.3 m to nearly 2 m in thickness, but only rarely exceed 0.8 m across. They commonly occur in swarms where they display a variety of peculiar and curious shapes that may or may not penetrate the entire seam (Fig. 13). Dikes commonly thicken and(or) thin abruptly and can be highly contorted, particularly where they are thin. Because Irregular-shape dikes are common, thick, and occur in swarms, they cause serious mine problems that include nearly the full range of mine problems discussed earlier.

CLASTIC SILLS, PIPES, AND ANOMALOUS DIKES

A very rare and anomalous dike that was studied in the Cameo Mine is mentioned separately because it does not fit into any dike category included in this text. The dike shown in Fig. 24 is termed a "spring dike" after its proposed mode of origin. This same style of dike was examined in the Deer Creek Mine outside of the town of Huntington, Utah (Fleck, written commun., 1993). Spring dikes are composed of two principal parts,

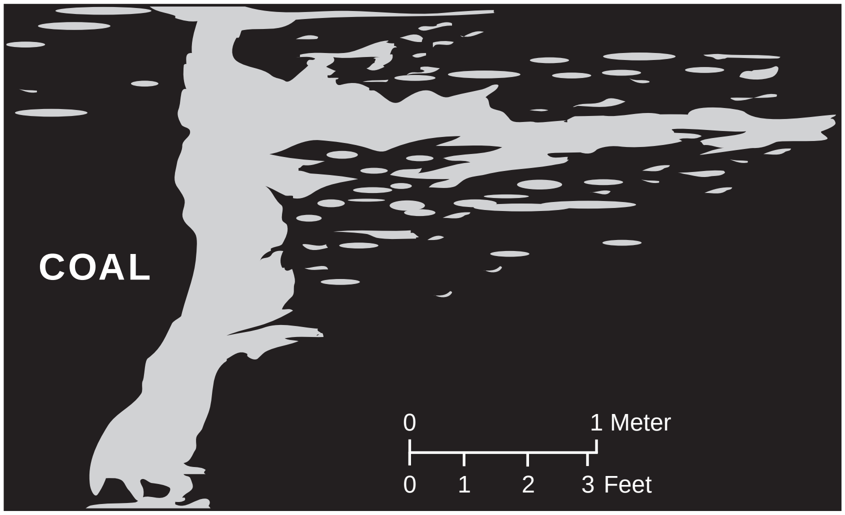


Figure 24. Sketch showing a rare dike that probably formed from a spring or boil within the peat

the "stem" and the "peripheral components." The stem penetrates from the floor to the roof at a near-vertical attitude and ranges in thickness from about 0.3 to 0.6 meters. The stem's contacts have a jagged to shredded character; abundant sill-like projections up to 3 m in length and more than 10 cm in thickness that extend outward from the stem along bedding planes in the coal (Fig. 24). Peripheral components include thousands of isolated, lense-shaped pods of dike material that display smooth contacts with the enclosing coal. They range in length from a few centimeters to 0.4 m and their thickness varies from several millimeters to several centimeters. Dike material is composed of siliciclastic sandstone that is indistinguishable from the underlying Rollins Sandstone.

These dikes are believed to have formed from a spring that was actively "boiling" within the peat swamp during and(or) immediately following the accumulation of vegetable matter. Guhman and Pederson (1992) reported that boils (actively flowing springs) in the Nebraska Sand Hills were as much as 10 m in diameter and 44 m in depth. Sand-sized particles were held in suspension in vertical conduits by upward-flowing ground water. The dimensions of the dike stem is consistent with measurements reported by Guhman and Pederson. The dike stem probably represents the vertical conduit that directed the flow of water and sand grains. The similarity of dike material with the Rollins Sandstone indicates that the boil probably formed from up-welling water produced from the dewatering of the Mancos Shale. The water carried sand grains in suspension from the Rollins. It is reasonable to conclude that the sill-like structures and the isolated, lens-shaped pods formed when sand grains were carried upward in the boil and deposited from suspension between loose flaps of peat that pulsated with changes in water velocity. Their lens shaped geometry and smooth convex upper and lower contacts probably resulted from subsequent peat compaction produced by sediment loading of the peat. The sill-like structures were probably the last features to develop. Sediment loading and volume loss of the peat squeezed the dike material outward from the stem along bedding planes in the peat.

Clastic sills and pipes are fairly uncommon features in western Colorado and have had little impact on coal production because of their small size and sparse numbers. Sills are typically found either attached to the terminus of pyramidal dikes or to large folds of dike material that extend horizontally into the coal (Fig. 13). Sills rarely extend more than a few meters horizontally, have sharp contacts, and display fairly constant thicknesses that generally measure less than 5 cm. Sills are secondary features that formed when dike material advanced along horizontal planes of weakness (bedding planes) within the peat as a result of volume loss of the peat caused by load compaction (Hardie, 1994).

Clastic pipes are isolated, ovoid-shaped sand bodies that measure less than about 15 cm wide and 10 cm in height. They occur as isolated features along the ribs of mine entries and cross cuts. Pipes probably formed in a fashion similar to that of clastic sills. Water-saturated dike material, which migrated vertically through the peat, intercepted horizontal zones of weakness that were shaped like long, rounded conduits. These conduits possibly formed from partially decayed logs, tree limbs, and(or) other coarse vegetable matter deposited in the peat swamp. Volume loss of the peat during subsequent compaction squeezed the dike material outward along these conduit-like structures. Further peat compaction flattened these features into ovoid shaped structures.

Mineralogy

Twenty-five stained thin sections of dike material and the underlying Rollins Sandstone were petrographically analyzed from the three study areas. Twenty-three thin sections were cut from samples taken from the southern two study areas and two thin sections were cut from dike material taken from the Craig study area. Because of the heterogeneity of dike material reported by Hardie (1994), many large samples were also analyzed by X-ray diffraction to determine their bulk mineralogy and later compared to point count results that were carried out using typical microscopy methods.

In the Craig study area, dike material consists of approximately 92 percent matrix-supported microcrystalline dolomite. The remaining material consists of about 6 percent very fine-grained quartz and trace amounts of chert and other lithic fragments. Dike material is well indurated, displays no visible pore space, and appears to be homogenous.

In the Palisades area, dike material consists of fine- to medium-grained, homogenous, siliciclastic sandstone with minor accessory minerals. Clastic material is mostly grain supported and is composed of 35–78 percent quartz, 14–36 percent cement and desegregated sedimentary rock material, 4–24 percent detrital and authigenic dolomite, 3–8 percent feldspar, 2–5 percent chert, and trace amounts of mica, siderite, and other lithic fragments.

Cement agents include ferroan and nonferroan dolomite, desegregated sedimentary rock material, and minor clay. Dolomite occurs in several forms that include aggregate and monocrystalline detrital grains, authigenic cement that contains rare poikilotropic fabric, and minor secondary dolomite that partially replaced feldspar, microcline, and quartz grains. Aggregate dolomite grains are sub-rounded to well-rounded and are composed of smaller detrital dolomite grains that range in number from fewer than ten to more than one hundred. Component grains can be composed of either non-ferroan dolomite, ferroan dolomite, or fractions of both. Monocrystalline detrital dolomite grains are rounded to sub-angular and may or may not display ferroan rims. Dolomite cement is commonly iron rich and displays an anhedral character that has filled nearly all visible pore spaces.

Fractured grains of detrital dolomite, feldspar, and quartz are relatively common and the voids separating grain fragments are commonly filled with iron rich dolomite showing that compaction pressure sufficient to fracture the grains was reached prior to formation of iron-rich dolomite. Quartz grains are mature and are composed mostly of monocrystalline grains having straight extinction; however, grains displaying undulose extinction are common. Polycrystalline quartz grains, which are less abundant than monocrystalline grains, display either sutured or straight boundaries. Grain contacts range from point to sutured to concavo-convex. Quartz grains joined by pressure solution appear to be fairly common. Quartz grains can display small vacuoles both as random features and as bubble trains. Both polycrystalline and monocrystalline quartz grains can display rims that are partially replaced by dolomite. Chert grains occur as either microcrystalline, macrocrystalline, or a combination of both. Sill material was analyzed and found to be very similar to dike material with the exception of higher percentages of fine-grained material.

In the Palisade study area, the Rollins Sandstone was sampled from cores taken from the Roadside North Mine and from nearby outcrops. Rollins Sandstone mineralogy and petrology are very similar to those of dikes in the Palisade area. The Rollins Sandstone is composed of 52–63 percent quartz, 15–36 percent cement and desegregated sedimentary rock, 1–3 percent detrital and authigenic dolomite, 3–8 percent feldspar, 2–4 percent chert, and trace amounts of mica, siderite, and other lithic fragments. The relatively low percentage of dolomite in the Rollins Sandstone is the principal difference between it and local dike material.

In the Somerset area, the mineralogy and petrology of dike material is similar to that found in the Palisades area. Dike material consists of siliciclastic sandstone composed of 40–65 percent quartz, 13–26 percent cement and desegregated sedimentary rock, 17–23 percent detrital and authigenic dolomite, 4–12 percent feldspar, 3–8 percent chert, and trace amounts of mica, siderite, microcline, and other lithic fragments. Cement includes ferroan and nonferroan dolomite, minor calcite, minor clay, and desegregated sedimentary rock material that have all but filled available pore space. Dolomite is found in several forms including aggregate and monocrystalline detrital grains, cement, mono-crystalline authigenic grains, and as partially replaced feldspar, quartz, and microcline grains. Authigenic monocrystalline grains occur as sharp-edged rhombs that display little or no abrasion. Descriptions for the remaining three forms of dolomite as well as the description of quartz grains are consistent with those described earlier in the Palisade. However, some especially large aggregate dolomite grains that tightly enclose adjacent quartz grains on three sides show that component dolomite grains became amalgamated some time after quartz grains were in place.

Dike material in the Somerset study area consists of at least two different lithofacies distinguished on grain size, percentage of matrix material, and whether or not they are grain supported. These two facies are not easily identified in the field. The *finer grained facies* consists of very fine-grained siliciclastic sandstone that is mostly matrix supported. In thin section, the matrix- supported material consists largely of desegregated sedimentary rock that causes the sample to appear grungy, indistinct, and difficult to analyze microscopically. In addition, unusually large, monocrystalline, detrital dolomite grains, as much as four to five times the diameter of adjacent quartz grains, are not uncommon. Quartz grains appear to be very angular; however, grain angularity may be an artifact of thin section preparation. The more *coarse-grained facies* is composed of fine-grained, grain-supported, siliciclastic sandstone. Matrix material is considerably less abundant than in the fine-grained facies and causes the dike material to appear clean and distinct in thin section.

In the Somerset study area, the Rollins Sandstone was sampled from cores taken from the West Elk Mine and from nearby outcrops. Like the Palisades area, the mineralogy and petrology of the Rollins Sandstone is very similar to those of dike material in the Somerset area. The Rollins Sandstone is composed of 38–59 percent quartz, 18–23 percent cement and desegregated sedimentary rock material, 9–17 percent detrital and authigenic dolomite, 3–12 percent feldspar, 1-6 percent chert, and trace amounts of mica, siderite, and other lithic fragments. The Rollins, like the dike material, is composed of either fine- or coarse-grained lithofaces. The composition of the Rollins Sandstone, including its two lithofacies, is nearly identical to the description given earlier in this section under "Somerset dike material" and is not repeated.

Coal Petrology

By Neely H. Bostick

Dikes in coal seams that are being mined or will be mined greatly influence the cost and safety of mining. The present shape and distribution of dikes are best determined if the way they formed is well understood. Analysis by use of a microscope adds much to what can be seen in the field. This analysis takes two forms: 1) structure and interrelation of dikes and the coal, described first, and 2) mineralogy and texture of dikes, described in the next section.

The general form of dikes seen in coal mines—dikes that cut across the coal seam nearly vertically—is seen in smaller scale in hand specimen (Fig. 25a) and under the microscope. However, the sinuous and crenulated structure of dikes, which causes them to appear folded, is seldom seen at small scales. The internal, natural layered structure of the coal adjacent to dikes shows that it is hardly disturbed (Fig. 25b, 25c, 25d). From this I conclude that much of the apparent sinuous nature of dikes is structure formed during highly fluid injection into a soft, fibrous peat. This conclusion is counter to the first impression, from seeing the sinuous dikes, that the sinuous structure reflects "folding" of dike walls during compression of the peat over thousands of years after the dike material was injected.

The layering in the coal, seen under the microscope, is solid vitrinite layers that formed from twigs and branches in the peat. These massive layers are sandwiched between layers of granular material formed by partly decomposed wood and leaf tissue mixed with naturally particulate plant material such as pollen and resin blebs. Most of the clay and other mineral matter, which forms the 5-10 percent mineral ash typically found when even good coals are burned, comprises the particulate layers. In Fig. 25b, the dike material cuts across the peat but disturbed it only by shouldering it aside, by wedging along a face formed when the peat was torn asunder. Fine stringers of peat are surrounded by mineral grains and "dented" by the grains, but they may persist as long stringers of coal far into the dike material (Fig. 25c). Locally, the peat was pushed aside strongly and some organic material may have been "stoped" away (Fig. 25d), but this seems to be uncommon.

In view of the evidence that the coal was in a peat or soft lignite stage when the dike material entered it, it is not surprising that some features seen under the microscope may have originated partly through compression of the organic matter long after the injection of dike material. Figs. 26a and 26b show mineral grains pushing into the organic matter and sometimes distorting it.

In order to see the relationships between coal and dike material accurately, we collected field samples oriented in space and made small cores from these to analyze under the microscope as shown in Fig. 27. Polished sections were cut at right angles parallel and across each core axis in order to examine local structures in three dimensions. Thus, in core one (Fig. 28) is shown a portion of the dike/coal contact cut across the core (the round parts) and the same portion cut parallel to the core axis (the straight parts). The fibrous organic matter lies still horizontal (note "up" in the figure), and the dike sands appear to have penetrated from right to left into the fibrous peat. Thus, though the general trend of this dike is NE-SW (in and out of Fig. 27), the local action of the sands at the point of Figure 28 was injection southeast here into the torn face of the peat.

Figure 29a shows the polished face of the same sample core at greater magnification, with the fine interfingering of the dike material and the coal layers. The fine detail of both the coal and the dike sand are visible in Figure 29b in three dimensions at still greater magnification. Even at this fine scale there was highly fluid penetration of the fibrous peat by water-saturated sand that formed the dike, with little distortion of the peat layers. Notice in the upper right of Figure 29b that "twigs" (now vitrinite) or less decomposed woody layers extend into the dike sands (See also Fig. 25c), presumably because their extra strength resisted tearing of the peat and erosion by the moving sand and water slurry. Fig. 30 shows a more complex site where the dike material and coal are in contact, including an "S" shaped dike structure that appears folded. However, the layers in the coal are still nearly undisturbed indicating that the "S" structure is not a fold, but rather an original, sinuous flow of the highly fluid sand slurry, much like toothpaste out of the tube.

In conclusion, microscopic analysis of the dike/coal contact and of the original layering preserved in the coal indicates features that must be taken into account in combination with the larger field features. The dike material penetrated the peat along irregular torn openings, which appear to have been mostly pull-apart openings, with little shear. The sands did little erosion or distortion of the peat layers and apparently were so fluid that they did not "stope" the peat. Locally, mineral grains press into the organic matter, but there is slight indication of differential compaction of the coal relative to the dike, and no examples of folded layering in the coal were found. These features seem to indicate that the physical behavior of the peat and dike material remained nearly alike (that is, both highly ductile) during burial by younger sediments and transformation of the peat into coal and the dike material into sandstone.

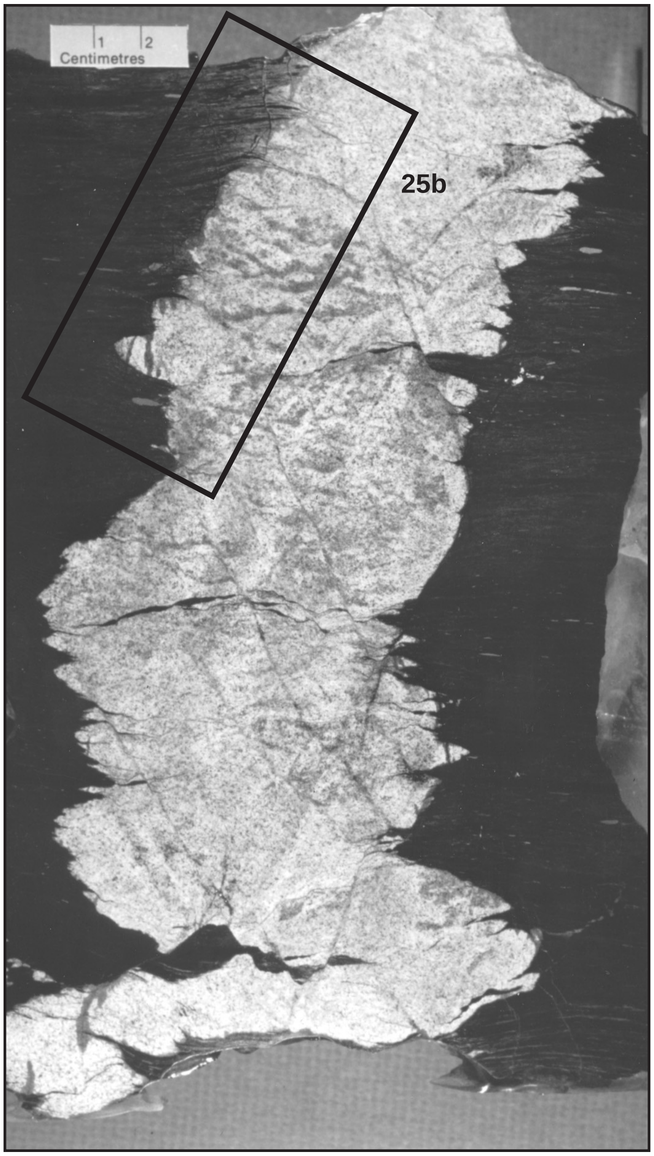


Figure 25a. Photo showing a block of rib rock from the Cameo Mine which contains part of a dike enclosed in coal. The block was sawed in half and polished. The general dike structure is irregular because the sand slurry spread to the side between layers of the peat/lignite in addition to the main penetration upward and in and out of the photo, forming the dike. The rectangle marks the position of Figure 25b.

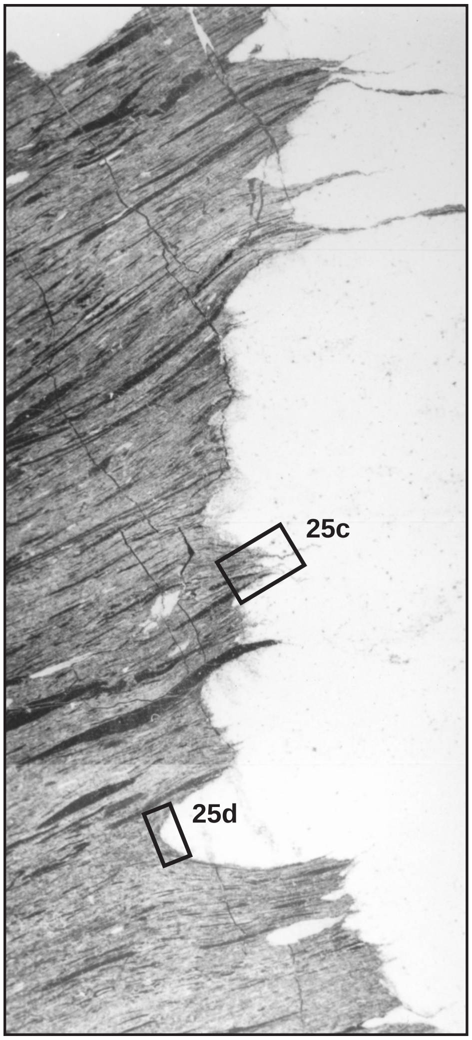


Figure 25b. At higher magnification (photomosaic width is 3.8 cm) the fine coal layers and the penetration by dike sand are clear. Rectangles locate areas shown in Figures 25c and 25d.

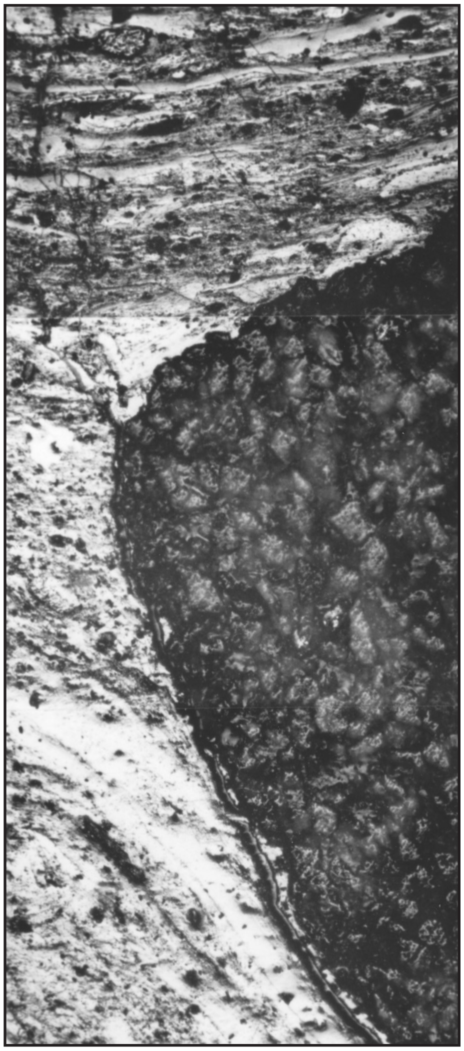


Figure 25d. Photomicrograph shows how dike sands locally removed peat/lignite material and pushed the remaining fibrous material abruptly aside. Width of sample shown is 2.7 mm, water immersion microscopy.

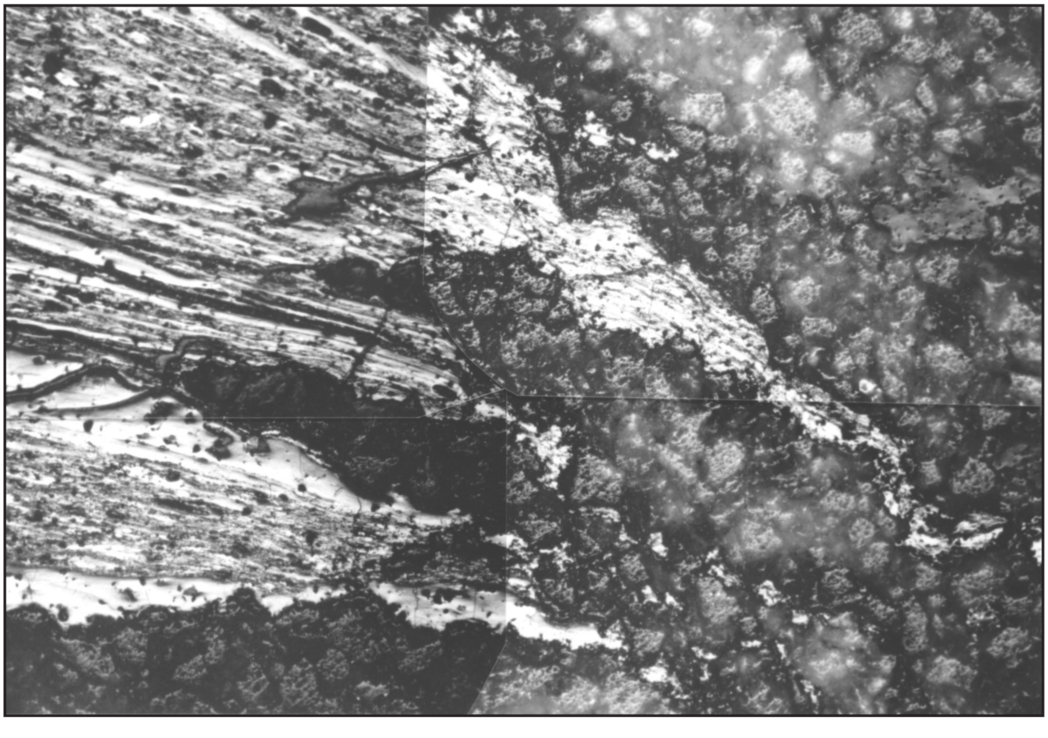


Figure 25c. Photomicrograph shows the individual sand grains in the dike material and the fine stringers of peat/ lignite "mat" preserved when the sand slurry was injected. Actual width of sample shown is 5.3 mm, water immersion microscopy.

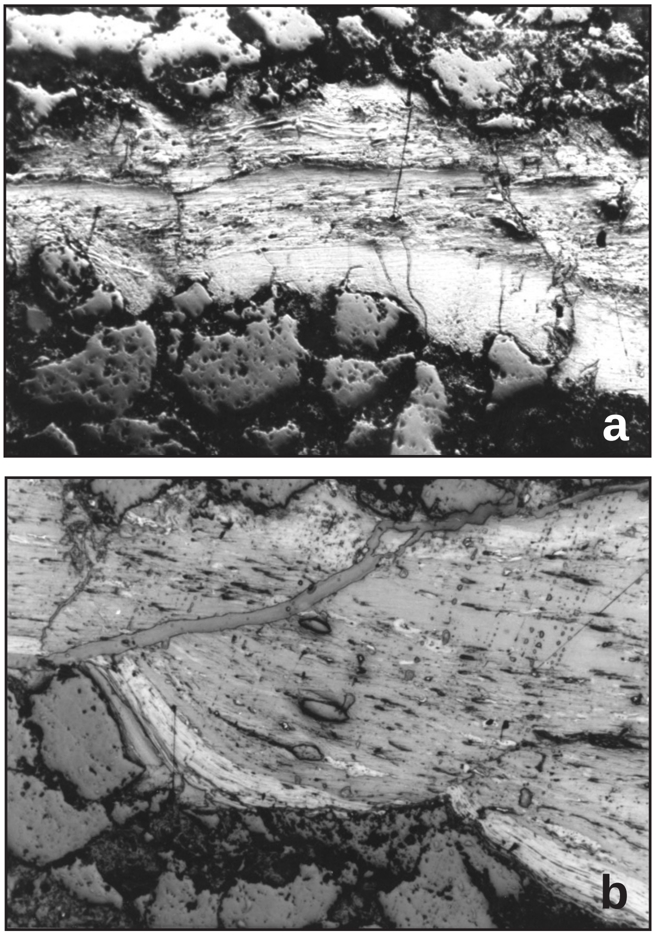


Figure 26a and 26b. Fine detail of a dike sample in polished section. The photo long dimension is 1 mm. Though the dike sands penetrated the peat/lignite layers and commonly left them undistorted, sand gains pushed into the soft organic material under the load of accumulated younger sediments.

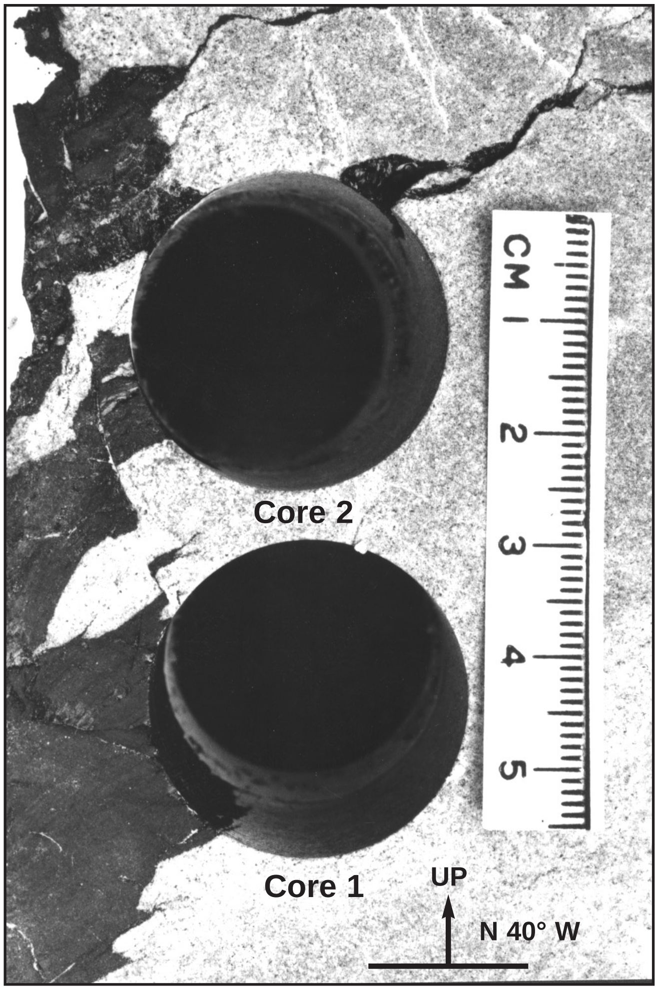


Figure 27. Dike sample cut horizontally across the dike trend. The orientation of the section is shown. Cores of the dike/coal contact were cut for microscope analysis. Core 1 at bottom, 2 at top.

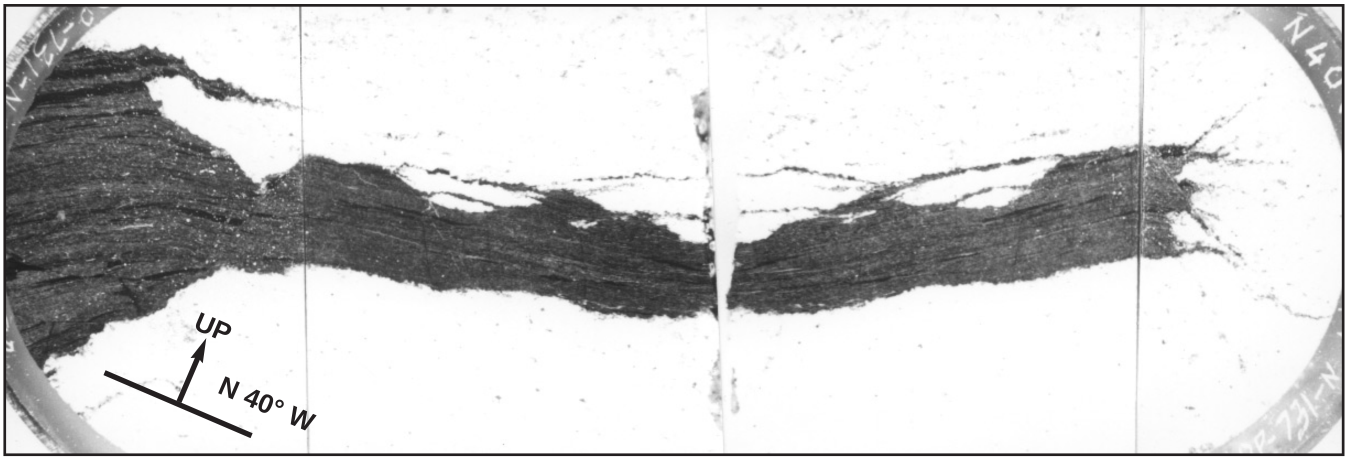


Figure 28. Closeup of core 1, cut and polished in two directions at right angles. The round sections joined are parallel to the face of Figure 27. The rectangular sections are oriented 90 degrees to each round section; they are opposite faces of the same vertical cut. The diameter of the core is 25 mm.

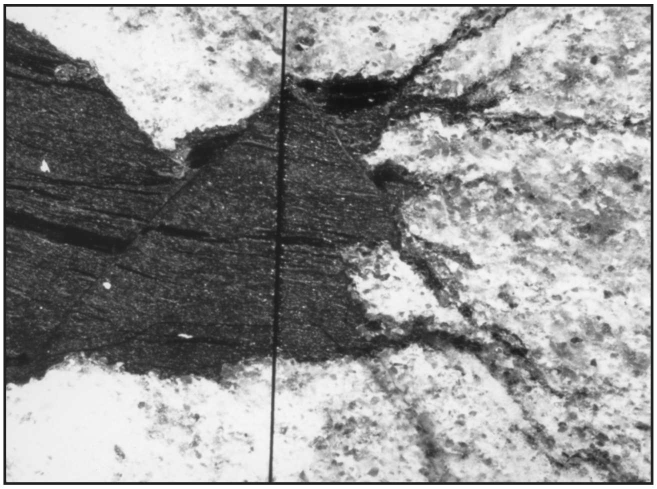


Figure 29a. Closeup of the center of the core section shown in Fig. 28.

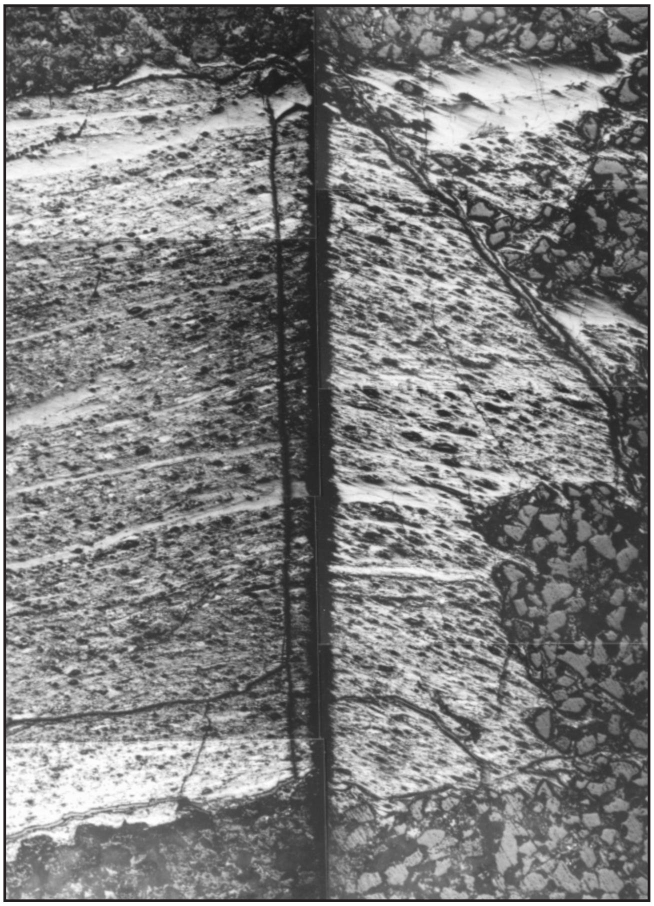


Figure 29b. Photomicrograph mosaic of the left half of the core shown in Fig. 29a (left), combined with the vertical section of the same area, right half of photo. Height of the photo is 7 mm; water immersion microscopy.

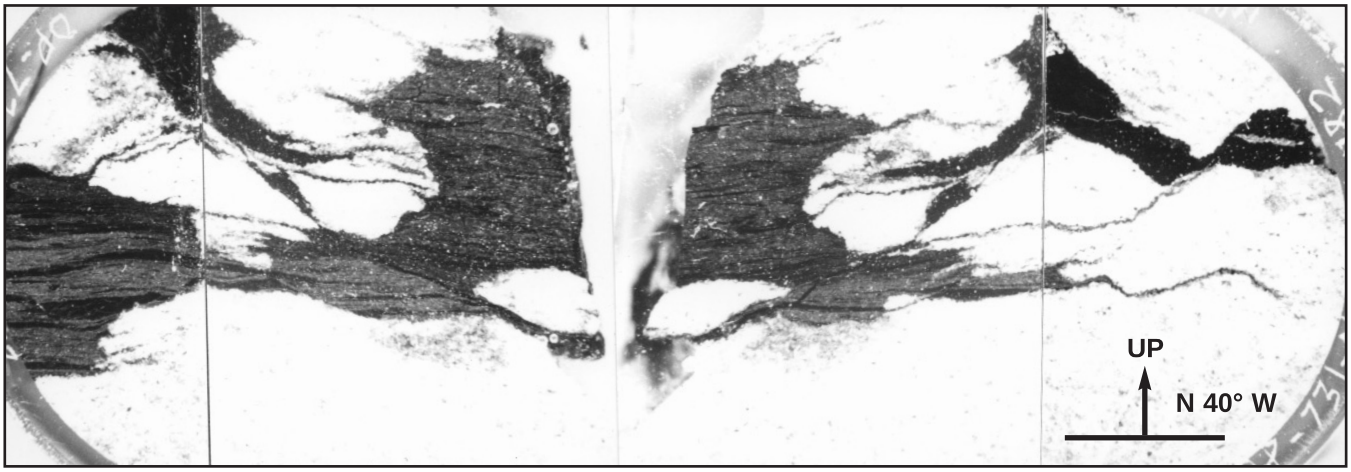


Figure 30. Closeup of core 2, cut and polished in two directions at right angles. The round sections are parallel to the face of Fig. 27; the rectangular sections are opposite faces of a cut at 90 degrees to the round section. The core diameter is 25 mm.

Interpretation and Discussion

Some question still exists among mine personnel of whether dikes formed by infilling fractures (or dessication cracks) from above, or by injection from below. The abundance of dikes that taper upward, particularly pyramidal- and some sigmoidal- and columnar-shaped dikes, strongly supports upward injection. Particularly, when considering that many broad based, joint-sourced dikes pinch out at some distance beneath the roof rock. Furthermore, hand samples of dike material and of the Rollins Sandstone examined under a hand lens were indistinguishable. Comparisons made under a petrographic microscope of analyzed thin sections of the Rollins Sandstone and dike material show that the two are nearly identical. In addition, observations of hundreds of dikes in outcrop, along strip mine floors, and along strip pit high walls shows that dikes were clearly injected from below coal seams and that the Rollins Sandstone was the source rock.

Clastic dikes were injected relatively early, probably under less than about 500 m of overburden. The absence of coal cleat that is partially filled with dike material shows that cleat development postdated injection. Close (1992) reported that much of the coal cleat development in the northern San Juan Basin is estimated to have occurred within about 4 million years after peat accumulation, and between 1.5 and 5.8 million years after peat accumulation in the Raton Basin. The near absence of microfaults along dike margins suggests that the coal was poorly coalified at the time of injection. Had the peat been well lithified, abundant high-angle microfaulting, produced by differential compaction, would be present at individual sites where wedge-shaped, interfingering, horizontal projections occurred along dike contacts. This observation is consistent with the lack of partially filled coal cleat, because coalification/lithificaton precede cleat development. The abundance of fine, coalified plant fibers preserved as stringers in dike margins shows that the coal was fibrous during injection and further indicates that the coal was either peat or soft brown coal at the time of injection. Although the maximum burial at which such injection could take place is not known, soft brown coals have as much as 50 percent moisture under 300 m of overburden and are somewhat fibrous (Teichmuller and Teichmuller, 1968). If one accepts approximately 300 m as a reasonable approximation of the maximum overburden, the presence of sills shows that injection pressure exceeded lithostatic load. Furthermore, if one accepts approximately 4 million years as reasonable timing for cleat development, the rate of sediment accumulation would have been roughly 0.075 mm per year.

Several lines of evidence indicate that dikes were controlled by two sets of joint fractures that are approximately normal to each other. The dominance of dikes that are both relatively straight and long is consistent with the geometry of joints (Figs. 4–8). Joints in the Rollins Sandstone, which are both heavily iron stained and bound by convolute zones interpreted as fluid escape features (Fig. 19), show that joints have provided avenues for the upward transmission of fluids at some earlier time. In addition, two iron-stained joints in the Rollins Sandstone that are physically connected to the base of a dike and that display approximately the same trend as the dike, are compelling. Another line of evidence is the similarity of dike trends measured at the Cameo, Cameo No. 1, Roadside North, Coal Canyon, and West Elk Mines (Figs. 4, 5, 7, and 8). It is noteworthy that dike trends shown in Figures 4–7 roughly agree with extension and release fracture trend data reported by Lorenz and Finley (1991). Lorenz and Finley reported that most fractures in the Piceance Basin can be attributed to generally west-northwest horizontal compression. Perhaps the strongest evidence that dikes were controlled by joint fractures is at the Coal Canyon Strip Mine where the bimodal orientation of fractures in the floor rock parallels the bimodal orientation of dikes (Fig. 7). Furthermore, dikes at the Coal Canyon Mine were directly observed emanating from joint fractures in the floor rock. The evidence indicates that joints acted as conduits for slurries of sand and formation water from below that were exhausted along the base of the overlying peat. It is probable that tears or vertical zones of weakness developed in the peat in response to the development of fracture joints.

Fractures in the roof rock probably provided some control for the formation of dikes. Dikes commonly form sharply bound, crude, zig-zag geometries visible along the roof that are interpreted as filled fractures (Figs. 14 and 15). Similarly, sharply bound cross-hatch patterns in the roof rock formed by the intersection of many small dikes are also interpreted as filled fractures (Fig. 16). The bimodal trend of these intersecting dikes, which is roughly common to the bimodal trends of dikes in nearby mines, suggests that the structural event that caused fracture joints to develop in the Rollins Sandstone also caused small-scale fracturing of the finer-grained roof sediments. The presence in the roof rock of undeformed, flat-lying, very thin laminae that were abruptly truncated against a dike shows that the roof was fractured and subsequently filled with dike material. If the roof was not fractured prior to injection, and the dike material forced its way through the roof sediments, the laminae would be distorted and bent upwards along dike margins. It is believed that roof fractures, which formed in poorly consolidated sediments, acted as low-pressure target sites for the upward migration of sand and water that was exhausted into the base of peat beds.

Many dikes observed underground formed from a secondary injection process in which dike material migrated horizontally through the peat. The presence of sills and pipes that are connected to dikes demonstrate that dike material migrated laterally. Figure 17 shows disjointed folds of a sigmoidal-shaped dike in the Roadside (south) Mine. This disjointed character could have formed only from the lateral migration of dike material from an unseen location within the coal seam where the dike was unbroken from floor to roof. Similarly, the two dikes in the left side of photograph shown in Figure 22 cut only the upper part of the coal seam and provide another example of lateral migration. None of the dikes shown in Figure 22 penetrated the roof, but instead they formed convex upward pressure points along the roof line as shown in Figure 20. The rose diagram showing the dike trends at the West Elk Mine includes a disturbingly large number of trends that lie between the dominant trends of N. 35° W. and roughly 0° N. (Fig. 8). These anomalous trends may have resulted from secondary injection. If this were the case, an unknown percentage of small-scale dikes were not directly controlled by joint fractures and, therefore, do not reflect the trend of fracture joints. It is believed that after dikes were injected, compaction and volume loss of the peat forced the water-saturated, compaction-resistant dike material to migrate laterally to form small-scale dikes. In some instances, particularly along bedding planes in the peat where coarse vegetable matter accumulated, dike material migrated along horizontal planes in a sheet-like fashion that produced sills. Roof fall problems, caused by sills located near the roof line, have been reported at nearly every mine in the Palisade and Somerset study areas.

Bostick (this report) stated that microscope examination of dike margins showed that the horizontal interfingering of fine stringers of organic matter with dike material indicated that the crenulated character of dikes (such as sigmoidal-shaped dikes) was produced by the upward migration of a highly fluid slurry of water and sand. It was further stated that compaction of the peat played no significant role in formation of this sinuous dike character. The author believes that Bostick's findings maybe an artifact of sampling. Bostick's field samples were probably gathered from locations where dike material migrated laterally (rather than vertically) and, therefore, do not show upward "bending" of fine organic matter that would have been present if samples had been taken at or near a site where dike material was injected vertically. Consequently, the sinuous character of some dikes may be a direct result of peat compaction.

There appears to be some agreement between the trend of coal cleat and that of joint fractures in the floor rock. It is widely accepted that face and butt cleat trends commonly are essentially parallel and perpendicular, respectively, to major structural trends. Similarly, face and butt cleat trends may, in part, be a function of joint development. At the West Elk Mine, face and butt cleat measure roughly N. 73° E. and N. 53° W., respectively, and primary and secondary joint trends in the roof strata measured N. 69° E. and N. 55° W. (Koontz, West Elk Mine, written commun., 1997). In the Palisade area, face and butt cleat measure N. 20°–50° W. and N. 65°–72° E., respectively. These trends are consistent with joint trends in the floor rock that measure N. 55° W. and N. 65° E. The apparent similarity of coal cleat, joint, and dike trends is noteworthy.

In summary, joint-sourced dikes are believed to have formed under the following conditions. Following shore line regression, and after deposition of the Rollins shoreface sand, peat swamps formed along the favorable platform produced by the upper bounding surface of the Rollins sand. Thick measures of peat accumulated and were subsequently buried under less than about 300 m of terrestrial sediments. Sediment loading resulted in volume loss and dewatering of the underlying Mancos marine shale. Dewatering produced an over-pressure condition within the Rollins sand, which was sealed by overlying accumulations of peat and organic-rich, fine-grained sediments. Fractures developed in unconsolidated floor and roof sediments, not unlike the multiple fractures that formed in unconsolidated sediments along the Cook Inlet of Alaska (a similar depositional environment) except that those fractures formed as a result of ground shock (Foster and Karlstrom, 1967). Fractures that formed in the overpressured Rollins sand probably tore apart the peat or created linear zones of weakness that provided avenues for venting slurries of water and sand into the base of peat beds. It is believed that this process produced the thick and laterally extensive dikes shown in Figures 4–8. Fractures in the roof sediments provided low-pressure target sites that further facilitated the upward migration of water and sand. Horizontal discontinuities in the coal, produced by either nondeposition of peat or by erosion-and-fill of the peat during fluvial incision, produced avenues in which to bleed off formation water from the Rollins sand. Bleed-off resulted in the development of wide areas and(or) linear belts that were relatively free of clastic dikes. Following the formation of dikes, accumulation of overburden resulted in coalification/volume loss of the peat. Dike material, being grain supported and hence resistant to compaction, responded to volume loss by migrating laterally along zones of relative weakness within the peat. In areas where roof fractures were absent, convex upward pressure points formed immediately above the path of laterally migrating dikes along the lower bounding surface of roof sediments (Fig. 21). Volume loss also resulted in the formation of sills and pipes that branch off from pre-existing dikes.

Fault-Fill Dikes

DESCRIPTION

Information on fault-fill dikes is less than complete because these dikes are rare and few have been directly examined in detail. However, they have been reported in greater numbers in coals of similar age that are outside our area of investigation in the coal district near Huntington, Utah (Hardie, 1994). Fault-fill dikes are unreported in the Craig study area but are probably present in sparse numbers. In the southern part of the Piceance Basin, such dikes occur in the Roadside (south), Cameo, Cameo No. 1, Roadside North, Somerset, West Elk and Sanborn Creek Mines. They appear to be more common in the West Elk Mine. Dikes occur as singular features that measure from about 15–80 cm across near the floor and can either thin upward to a terminus near the upper portions of coal seams or penetrate into the roof (Fig. 10). Parts of individual dikes are commonly composed of poorly indurated sandstone and(or) sandy claystone. Other parts, particularly near the terminus, are composed of claystone, mudstone, or well-indurated sandstone. The lateral extent of fault-fill dikes is not known, although it is believed that they extend hundreds of meters. Dikes cut coal seams at high angles and are sharply bound along their uppermost contact by high-angle, normal faults. Mostly faults cut entire coal seams and display tens of centimeters of displacement that commonly dies out near or just above the roof line. The lower contact of the dikes exhibits an irregular and undulate character and displays no visible signs of faulting (Fig. 10).

INTERPRETATION

Fault-fill dikes were injected from below, relatively late, well after initial coalification of peat beds. Their tendency to thin upward and pinch out near the top of coal seams indicates that dike material entered the coal seam from below. Their sharp, fault-bound, upper contact indicates that the coal, at a minimum, was a medium rank lignite when it was intruded. Had it been peat-like, the sharply bound upper contact would have been replaced with a near vertical zone where stretching, tearing, and deformation of interwoven plant matter would have absorbed much if not all of the offset movement. In addition, one would expect to see strong evidence of peat compaction including dike swelling, coal fishtails, bulbous accumulations of dike material along or adjacent to the dike, and(or) dike crenulation. The presence of a single, fault-bound, contact opposite an undulate contact suggests that offset occurred either during or after injection. If clastic material were injected into a fracture that was already faulted and where no further offset movement were to take place, both dike contacts would display a similar undulate character. At the time of injection, both contacts probably had a similar undulate character, but continued faulting probably smoothed out and healed those irregularities along the upper fault-bound contact. Fault-fill dikes have little impact on mining because they are rare and relatively small; therefore, they warrant little more discussion.

Channel-Margin Dikes

DESCRIPTION

Channel-margin dikes are believed to be present in varying numbers in all coal mines within these three study areas. They are probably more abundant than reported because they are generally small features that have little impact on coal production and are often ignored or go undetected during mining. Most dikes are solitary intrusions but they are also found in multiples (Fig. 9). They are nearly always attached to sandstone channel bodies in the roof and taper downward to a terminus within the upper meter of coal seams. Channel-margin dikes rarely exceed 5 cm in thickness and seldom extend more than about 20 m laterally. Their angle of penetration ranges from nearly horizontal to vertical. High-angle dikes, less than about 30 degrees, can display poorly developed crenulation. Low-angle dikes have more uniform thicknesses and display nearly smooth contacts. Commonly, dikes can be traced 10-20 cm downward from their attachment point at the base of channel bodies where they abruptly change to a horizontal attitude that parallels the base of the channel. Coal banding commonly conforms to the geometry of channel bodies.

Petrographic analysis shows that the compositions of individual dikes and their associated channel sandstone body are indistinguishable. Dike material is primarily composed of clean, grain-supported, mature, quartzose sandstone that commonly contains minor amounts of detrital and authigenic dolomite.

INTERPRETATION

Channel-margin dikes probably developed earlier than both joint-sourced dikes and fault-fill dikes. The absence of well-developed crenulated character in high-angle dikes suggest that dikes formed after significant compaction of the peat. The widespread association of dikes with roof channels, particularly those that are attached to the margins of channels, and the similarity of the dike material composition and that of the channel bodies demonstrate that channel bodies are the source material of dikes. Coal banding that conforms to the shape of overlying channel bodies indicates that channel bodies were pressed into the upper surface of peat beds by the weight of the overlying sediments. Channel bodies, composed of grain-supported material, experienced little compaction and “flattening-out” as they were pressed into peat beds. The shallow and nonlinear penetration of dikes into the tops of coal seams and their attachment to channel bodies suggests that dikes formed from infilled tears in the peat. Once the tears were filled with channel material, continued sediment loading and compaction of the peat probably squeezed clastic material farther into the peat. Kerns (1970) proposed a similar control for dikes associated with floor and roof rolls in the Pittsburgh coal seam of southwestern Pennsylvania. He suggested that tension cracks developed in areas adjacent to sand bodies where the peat was stretched and filled with sediments. Tectonics probably played no direct role in the formation of channel-margin dikes as evidenced by the apparent randomness of dike trends and their relatively short lateral extension. Channel-margin dikes have a minimal impact on coal production because they are small and occur only in the upper meter of coal seams.

Mining Strategies and Significance of Dikes

Within the three study areas, clastic dikes are believed to have at least three principal modes of origin. Channel-margin dikes were probably the earliest to form, at a time when organic matter was still in the peat stage and buried under less than about 100 m of sediments. Joint-sourced dikes formed somewhat later, while the organic material was buried under several hundred meters of sediments and was approaching the soft brown coal stage. Fault-fill dikes were probably the last to form, after considerable sediment loading and coalification. Contradictory evidence of dike genesis within the same study area suggests that dike formation involved more than one process during more than one time period. In addition, petrographic examination of dike material and source rock may find significant mineralogic and petrographic differences. Greater stratigraphic intervals between the source rock and the dikes provide greater opportunities for contamination of dike material by the intervening strata and the fluids they transmit.

Clastic dikes have created severe problems in underground and surface coal mines that have resulted in mine closure and injury of mine workers. Where dikes are present in numbers and(or) have thicknesses greater than about 0.3 m, recommended mining strategies include excavating the coal so that the working face or long wall is at a high angle to the central trend of dikes. Similarly, roof failure related to the cantilevering of roof rocks along zones of weakness at dike contacts can be reduced by driving mine entries at high angles to the central trend of dikes to reduce dike alignment with main entries. Where continuous miners are used and where possible, coal should be excavated from the top, working downward. This facilitates dike extraction by removing or "pulling-down" large blocks of dike material, particularly in the upper parts of coal seams. The "weighting" of continuous miners reduces the bouncing and vibration that the equipment typically experiences while cutting dikes. Experimentation with cutting tools is an obvious consideration, particularly where dikes are well indurated and(or) cemented with dolomite.

The various forms of dolomite found in western Colorado dikes are of particular interest because of their environmental implications. The presence of dolomite-rich dikes in peats that accumulated along paleoshorelines that were repeatedly transgressed suggest that sea water provided magnesium necessary for the precipitation of dolomite. Land (1985) proposed that seawater is the only common magnesium-rich fluid in the earth's crust and must be the primary agent for the formation of dolomite. He went on to say that dolomite must form relatively early in the depositional history of sediments, when sea water or sea water-derived fluids can be actively pumped through sediments. Sibley (1991) wrote that if one accepts Land's proposition, then the optimal situation for dolomitization is prolonged sea level highstands or slow subsidence. The marginal marine coals in these three study areas fit well into Sibley's "optimal situation." In addition, the acidic nature of peat swamps and the early injection and precipitation of dolomite are an interesting apparent geochemical contradiction.

Clastic dikes are common in many North American basins where coal seams are associated with marine sequences and are uncommon to absent where coal accumulated in continental settings. Few if any dikes are reported in alluvial plain coals, such as those found in the Powder River Basin, Williston Basin, and Denver Basin. Dikes are common in many marginal-marine coals including those in the Appalachian Basin, Illinois Basin, Unita/Piceance Basin, and particularly those coals that accumulated directly on shoreface deposits. This association is probably related to one or more factors including sustained water production through dewatering of the underlying marine shales, overpressured sand bodies beneath coal seams, and differential compaction of marginal-marine sediments.

Only through cooperative studies that rely heavily on providing future investigators with access to mined areas that are highly intersected with clastic dikes can a greater understanding and a more comprehensive paradigm of dike formation be developed.

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