ENVIRONMENTAL GEOLOGY OF ABANDONED LIGNITIC- AND BITUMINOUS-COAL MINES OF TEXAS

APPROVED:

ENVIRONMENTAL GEOLOGY OF ABANDONED LIGNITIC- AND BITUMINOUS-COAL MINES OF TEXAS

BY

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THESIS

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My introduction to the environmental geology of abandoned coal mines in Texas came when I was first employed by the Bureau of Economic Geology. Robert J. Finley (Research Scientist) and William H. Hupp (now with the Texas Department of Water Resources) had just begun to assess conditions at mine sites in North-Central Texas when I was given a place in that project. The work was grist for my mill and research for my thesis really began then. Under Rob Finley's able supervision Bill Hupp and I spent weeks in the field and more weeks peering through stereoscopes at tattered, fading aerial photographs. We discovered that the subject was enticingly complex and my interest was secured. This thesis holds the stamp of my former coworkers as well.

Present and former personnel of the Railroad Commission of Texas, Surface Mining and Reclamation Division, also lent a hand. Vika Newsom and Larry Smith, both now elsewhere, were my first contacts at that agency. James Sansom and Deborah Kocurek are with the Commission still. Each of these individuals showed the kind of cooperative purposefulness that would be a model for interagency research programs.

Field investigation of abandoned mine sites requires access to private property, and initially this was a major concern. However, landowners throughout the state were extremely receptive. Not once was I denied access. Instead I frequently was invited into the homes of these farmers and ranchers and given the benefit of their thorough knowledge of the local area and its mines. Three individuals deserve special attention here: Ebertt Pitts, Bridgeport; Allard Smith, Jacksboro; and P. D. "Pink" Wylie, Mingus. Each is a retired miner or other mine worker and

each freely shared his experiences and patiently answered my many questions. One other landowner also must be mentioned: Sam Hays, Lohn. Mr. Hays was tour guide and teacher through many hours in the heat of summer. Under his gentle tutelage I discovered the palpable presence of history. These were lessons I will never forget. They too are here in my thesis.

Kay Caran typed the draft manuscript and Millie Wendell typed the final edition. Drafted figures (except as noted) were prepared by John Cotter from original maps and drawings by Chris Caran. Most of the photographs were taken by Chris Caran. Other photographers are acknowledged in the figure captions. Nan Hampton and Dr. John Ellison arranged for access, assistance, and materials for use of the scanning-electron microscope in the Zoology Department, The University of Texas at Austin.

So many others have assisted in ways too numerous to count. Members of the faculty of the University of Texas and researchers at the Bureau of Economic Geology deserve special acknowledgment, as do personnel of the Texas Natural Resources Information System and Soil Conservation Service. Librarians throughout the University System, state and federal agencies, and several communities were ever helpful. My appreciation is sincere: thanks to all.

In my travels and endless hours of reading, writing, trying to understand I was never very far away from the three people most dear to me. My wife Kay and daughters Abby and Libby will be the happiest to see this final page typed and the bindings sewn. It is they who made it possible and it is to them I offer my dedication.

ABSTRACT

Lignitic, canneloid, and bituminous coals have been mined in Texas since at least the early 1800's and possibly the 1750's. Inactive mining districts are located in most regions of the state and mining continues in several areas. The mined seams of coal lie within sedimentary sequences of the Upper Pennsylvanian, Upper Cretaceous, and lower and middle Eocene Series. Most of the production before 1924 was from underground mines, whereas all coal extracted since the late 1940's has come from surficial mines. Prior to the 1970's, few mines were reclaimed. Consequently, many sites of abandoned coal mines in the state exhibit a wide range of adverse, environmental-geologic conditions, varying both in type and intensity. Conditions at these sites include: subsidence and faulting; effects of combustion; production of toxic, geochemical leachates; erosion, sedimentation, and effects on drainage; and the presence of open mine shafts, structural and mechanical debris, large spoil mounds, and miscellaneous refuse. Quantitative assessments of these conditions at selected sites were qualitatively extrapolated to other areas to permit evaluation of conditions statewide. Some of

the most severely affected sites have been reclaimed under the regulatory authority of the Railroad Commission of Texas and by the U.S. Soil Conservation Service. Of the more than 260 sites of abandoned coal mines in Texas perhaps one-fourth eventually may require some corrective attention.

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INTRODUCTION

Many of the abandoned coal mines in Texas exhibit a combination of adverse, environmental geologic conditions generally associated with better known mining districts in Appalachia and the western U.S. These conditions include erosion and sedimentation, effects on runoff, acidic mine drainage, subsidence, and underground combustion. The intensity of these effects at sites in Texas ranges from negligible to locally severe. Health and safety hazards are evident at a few sites but environmental impact on land and water resources is the principal cause for concern in most areas. Among the most significant problems is the erosion of mine spoil. This effect is heightened by devegetation resulting from the formation of phytotoxic geochemical leachates. Other conditions are important locally.

The purpose of the present study is to identify the cause of these and other problems, the natural processes that reduce or magnify their impact, and the severity of effects. To these ends extensive investigations in the field have been combined with interpretation of hundreds of aerial photographs, limited studies in the laboratory, and a fairly comprehensive review of the relevant literature. All known abandoned coal mines in the state are treated in this study although the level of treatment varies. For example, about one-third of the sites were not visited. Yet to the extent possible this discussion summarizes most of what is known about conditions at all sites based on data from many sources.

Prior to the introduction, in 1975, of State regulations mandating reclamation of sites of coal mining in Texas (concomitant Federal regulations were issued in 1977), most of the more than 260 inactive coal mines in the state simply were abandoned when operations terminated (Newsom, 1979; Caran, 1981). No deliberate effort was made to restore a site to its original condition, and only rarely were private covenants successful in returning mined lands to productive use. Some sites were reclaimed through the years by landowners. More often, however, mine sites either deteriorated or recovered naturally with little or no management.

The period of concerted mining before the mid-1930's was an especially fascinating historical episode with an unfortunate modern legacy. Adverse conditions exist at many of the mines dating from this era and at some mines developed in later years. The location and condition of most of these abandoned mines were little known before the issuance of a report by the Bureau of Economic Geology (Finley, Caran, and Hupp, 1979) on mine sites of North-Central Texas. The report was prepared for the Railroad Commission of Texas. This state agency is responsible for licensing new mines and administering funds to reclaim older, severely affected sites of coal mining. While Finley and his coworkers were conducting their survey, the staff of the Surface Mining and Reclamation Division of the Railroad Commission (particularly Vika Newsom and Larry Smith) engaged in a similar effort in other parts of the state. The Railroad Commission's own inventory was not published in any form. However, the information was kept on file and supplemental data has been added to these preliminary records by other investigators.

The two surveys of abandoned mines that were begun in 1979 constitute the starting point from which the present study developed. I revisited many of the mine sites throughout the state and gathered most of the primary data actually incorporated in this thesis. In the process a few unreported mines were found and described and several erroneous reports were corrected. I also reviewed the extensive but widely scattered literature concerning coal mining in Texas. There is evidence that the history of coal mining in the state is much longer than was indicated by previous investigators.

The present study has disclosed the range and intensity of conditions at mine sites throughout the state. One practical outcome of this investigation was the development of a method for determining the temperatures attained in underground fires, either in mines or spoil mounds. Knowledge of these temperatures and the lateral extent of areas of combustion could aid efforts to control such fires and would be particularly useful in reclaiming abandoned mines. This and other observations that are especially relevant to reclamation are summarized in the final section of this report.

Measures to abate hazards and restore productivity eventually may be required at several of the state's mine sites in addition to those already reclaimed. The most telling, present needs are for detailed characterization of geochemical leachates, hydrologic conditions, and the petrology of spoil. Perhaps the current study may stimulate additional investigations along these lines.

COAL IN TEXAS

Resources

Accessible seams of coal in Texas are among the most extensive in any area of the United States. The U.S. Bureau of Mines and U.S. Geological Survey (1976, p. B1) define "resource" as a concentration of a mineral commodity in such form that economic extraction is currently or possibly feasible. This definition is the basis of standards established by the U.S. Geological Survey for assessing mineralic deposits (Averitt, 1961, p. 18, 20-21). In accordance with these standards Mapel (1967) and Kaiser and others (1980) estimated that Texas has 58,300 million metric tons (64,300 million tons) of lignitic, bituminous, and canneloid coal. These estimates exclude all deposits of peat, as well as all coal in seams of less than the minimum thicknesses or more than the maximum depths specified by Mapel (1967) and Kaiser and others (1980). All of the seams included in the estimates are more than 35.6 cm (14 inches) thick and less than 915 m (3,000 ft.) deep. The combined, areal extent of these resources is greater than 26,250 km^2 (10,500 mi^2). Coal is found in all regions of the state except the Panhandle and part of Central Texas, although seams are sparsely distributed through the Trans-Pecos (fig. 1).

Stratigraphy

Seams of coal in Texas lie within thick sedimentary sequences of the Upper Pennsylvanian, Upper Cretaceous, and lower and middle Eocene Series (fig. 2). Figure 2 is drawn largely from works by Evans (1974) and Kaiser and others (1980). Evans (1974) reviewed and summarized the most important literature pertaining to the stratigraphy of bituminous and canneloid coals of North-Central, West, and Southwest Texas. The stratigraphic framework of the Pennsylvanian System of North-Central Texas follows that of Kier and others (1980). Kaiser and others (1980) have investigated the stratigraphy of deposits of Eocene lignite, revising and redefining previous concepts. No effort was made in the present study to systematically review the data contained in these published reports. However, where pertinent observations were made in the field, they confirmed these earlier findings.

The environments of deposition and geometries of coal-bearing units in Texas are described by Mapel (1967), Evans (1974), and Kaiser and others (1980). Most of the

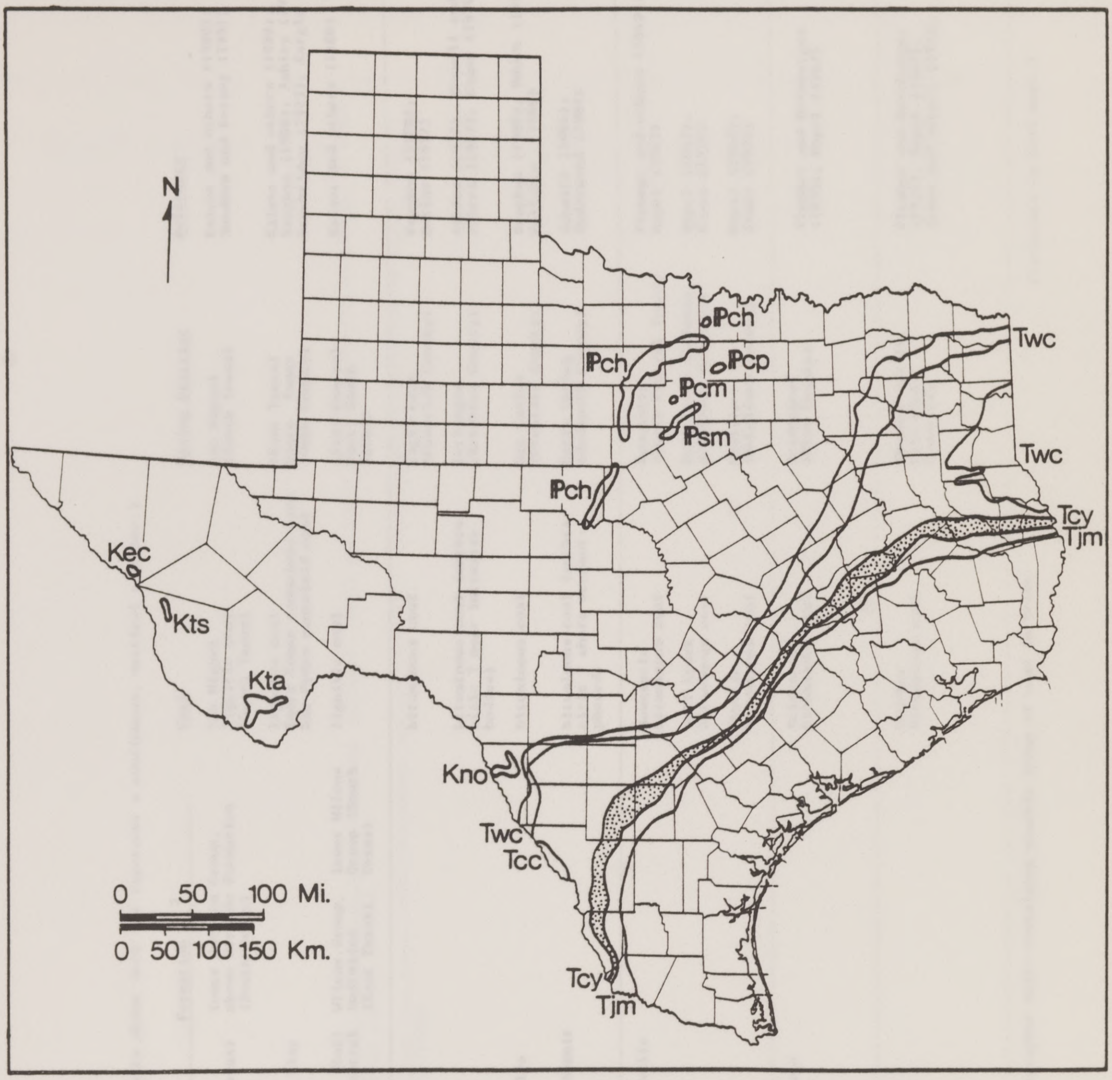


Figure 1: Minable seams of coal in Texas: Tjm, Tertiary Jackson (Manning); Tcy, Tertiary Claiborne (Yegua); Twc, Tertiary Wilcox (Calvert Bluff); Kno, Cretaceous Navarro (Olmos); Kta, Cretaceous Taylor (Aguja); Kts, Cretaceous Taylor (San Carlos); Kec, Cretaceous Eagle Ford (Chispa Summit); Pch, Pennsylvanian Cisco (Harpersville); Pcp, Pennsylvanian Canyon (Palo Pinto); Psm, Pennsylvanian Strawn (Mingus). Adapted from St. Clair and others (1976).

(Succession of units shown does not represent a continuous, vertical sequence.)

System	Series	Group	Formation [1, 2]			Coal	Mining District	Reference
Tertiary	Eocene	Jackson	Manning (East Texas)	lower Jackson Group, above Mirando Formation (South Texas)		San Miguel lignitic coal (South Texas)	San Miguel (South Texas)	Kaiser and others (1980); Snedden and Kersey (1981)
Tertiary	Eocene	Claiborne	Yegua El Pico Clay Bigford			lignitic coal Santo Tomas canneloid coal San Pedro canneloid coal	(East Texas) Santo Tomas (Webb County)	Kaiser and others (1980); Vaughan (1900); Ashley (1919); Trowbridge (1923); Eargle (1968)
Tertiary	Eocene	Wilcox	Calvert Bluff (East-Central Texas)	Wilcox Group, Undivided (East Texas)	lower Wilcox Group (South Texas)	lignitic coal	(East-Central, East, South Texas)	Kaiser and others (1980)
Cretaceous	Upper Cretaceous (Gulfian)	Navarro	Olmos			bituminous coal	Eagle Pass (Maverick County)	Vaughan (1900); Adkins (1932)
Cretaceous	Upper Cretaceous (Gulfian)	Taylor	Aguja			bituminous coal (anthracitic ? near intrusive bodies)	Terlingua (Brewster County)	Adkins (1932); Maxwell and others (1967); Evans (1974)
Cretaceous	Upper Cretaceous (Gulfian)	Taylor	San Carlos			bituminous coal	San Carlos (Presidio County)	Vaughan (1900); Udden (1913); Wolleben (1966)
Cretaceous	Upper Cretaceous (Gulfian)	Eagle Ford	Chispa Summit			bituminous coal (anthracitic ? where metamorphosed)	Eagle Spring (Hudspeth County)	Schmitz (1885); Underwood (1962)
Pennsylvanian	Virgilian	Cisco	Harpersville			Newcastle bituminous coal	Newcastle (North-Central Texas)	Plummer and others (1949); Mapel (1967)
						Bull Creek bituminous coal	Bull Creek (Coleman, McCulloch Counties)	Mapel (1967); Evans (1974)
						Chaffin bituminous coal	Chaffin (McCulloch County)	Mapel (1967); Evans (1974)
Pennsylvanian	Missourian	Canyon	Palo Pinto			Bridgeport bituminous coal	Bridgeport (Wise County)	Plummer and Hornberger (1935); Mapel (1967)
Pennsylvanian	Desmoinesian	Strawn	Mingus			Thurber bituminous coal	Thurber (Erath, Palo Pinto Counties)	Plummer and Hornberger (1935); Mapel (1967); Brown and others (1973)

Figure 2. Stratigraphic units containing minable seams of coal in Texas.

(Footnotes on next page.)

[1]Only those coal-bearing units with a history of mining are included. Coals for which there is no record of mining, or which have received only trivial use are omitted.

[2]Compilation derived in part from Evans (1974) and Kaiser and others (1980). Treatment of the Pennsylvanian System follows that of Kier and others (1980).

coal accumulated in fluvial, deltaic, or lagoonal environments. Conditions under which organic parent materials were deposited and the composition of those materials control to a great extent the type and quality of coal.

HISTORY OF COAL-MINING AND MINING METHODS PRACTICED IN TEXAS

Early Mining, 1750-1830

The history of coal mining in Texas is marked by periods of intense activity punctuated with intervals of diminished production and even virtual quiescence. Efforts to develop the state's enormous reserves generally have fluctuated in inverse proportion to the availability of other fuels that could be produced less expensively. This relation was observed by Phillips in 1902 (p. v, vi) and remains true today.

There is no known ethnohistorical account or other direct evidence to indicate that Indians mined coal in Texas prior to European settlement (Henderson, 1964; Betancourt, 1977). It is unlikely that these Indians would have depended on coal as a fuel because firewood and other flammable materials were more readily accessible. In addition, aboriginal technology did not require a highly efficient or intense source of heat. However, Henderson (1964, p. 208 and 213) and Betancourt (1977, p. 67) have argued that some of the state's Indian populations (at least those in areas where seams crop out) probably were aware of coal and its combustible properties. Charred lignite has been found in

Precolumbian hearths excavated in Venezuela and Alabama (Salvatore Valastro, personal communication, 1983). Jesuit missionaries reported in 1660 that Algonquian tribes along the Mississippi River made "fire with coal from the earth" (Rickard, 1932, p. 14-15), and Friar Louis Hennepin actually observed Indians digging coal near the Illinois River in 1679 (Hennepin, 1903, p. 152). Pedro de Castaneda's narrative of Coronado's expedition through Texas and the American Southwest from 1540 to 1542 contains evidence of at least some contact between the Indians of Texas and those living in the area of the Arkansas or Mississippi Rivers (Castaneda, 1907, p. 330). Thus, it is possible that Texas Indians made sparing use of fragments of coal collected or dug from natural exposures. There is no reason, however, to suspect that such excavations were extensive, and certainly, all evidence of their existence was obscured long ago.

Stenzel (1946, p. 197) stated that the earliest definite record of exploitation of coal in Texas is that of a "mine de charbon de terre" (coal mine) denoted on a map accompanying a report by L'Heritier (1819). L'Heritier (1819, p. 96-99) also discussed the state's mineral resources and the legends concerning mineral wealth that were prevalent even then. The mine shown on L'Heritier's map was located "about 25 leagues (approximately 106 km or 66 mi) east of Trinity River and about 27 leagues (approximately 114 km or 71 mi) west-northwest of the presidio of Chichi on the branches of the Sabine River in East Texas" (Stenzel, 1946, p. 197). The coal (lignite) apparently was produced from either the Eocene Yegua Formation (Claiborne Group) or the Wilcox Group (fig. 1).

However, the oldest coal mine in Texas actually may have been located along the Rio Grande. Berlandier (1980, p. 265), writing in 1829, described an abandoned mine at the town of Palafox, a small community on the eastern bank of the Rio Grande in the Santo Tomas cannel-coal mining district of Webb County (see Ashley, 1919, plate 29). Palafox was founded in 1810 and abandoned in 1818, and was not regularly reoccupied until much later (Branda, 1976, p. 691). Thus, the mine could have been opened as early as 1810 or before, and almost certainly before 1818, possibly making it as old or older than the mine noted by L'Heritier (1819).

But, Berlandier (1980, p. 426, 427, 584-587) also described one or more coal mines at Revilla in Tamaulipas, Mexico. Roemer (1935, p. 10), writing in 1849, stated that "a rich bed of excellent coal" had been discovered some years earlier near Revilla. This community was located along the Rio Grande, at a site now inundated by Falcon

Reservoir (Branda, 1976, p. 433), on the western bank of the river across from Dolores townsite in Webb County (*see* Ashley, 1919, plate 29). Dolores also was an early mining community. Coal was mined there before 1836 and Ashley (1919, p. 269) noted that a cannel-coal mine at nearby Darwin was "said to be the oldest (mine) in the State." These mines probably were developed soon after the founding of Revilla and Dolores in 1750, for within the large colony of Nueva Santander (encompassing most of northeastern Mexico and south Texas) in which these settlements were established, eleven mines of unspecified type and location had been opened by 1757 (Bolton, 1915, p. 292 and 297-300). The namesake of the colony, Santander Province in Spain, is a major coal- and iron-producing region. Coal mines at Revilla and possibly Dolores already were well established when Berlandier (1980, p. 426-427 and 584-586) described them in 1829 and again in 1834. The existence of cannel-coal mines on the banks of the Rio Grande in the middle to late 1700's or very early 1800's tends to corroborate the suggestion that South Texas may have been the first coal-mining district in the state. The coal was mined from short drifts (fig. 3) extending into outcrops of the Bigford and El Pico Clay formations of the Eocene Claiborne Group, at Palafox and Dolores, respectively.

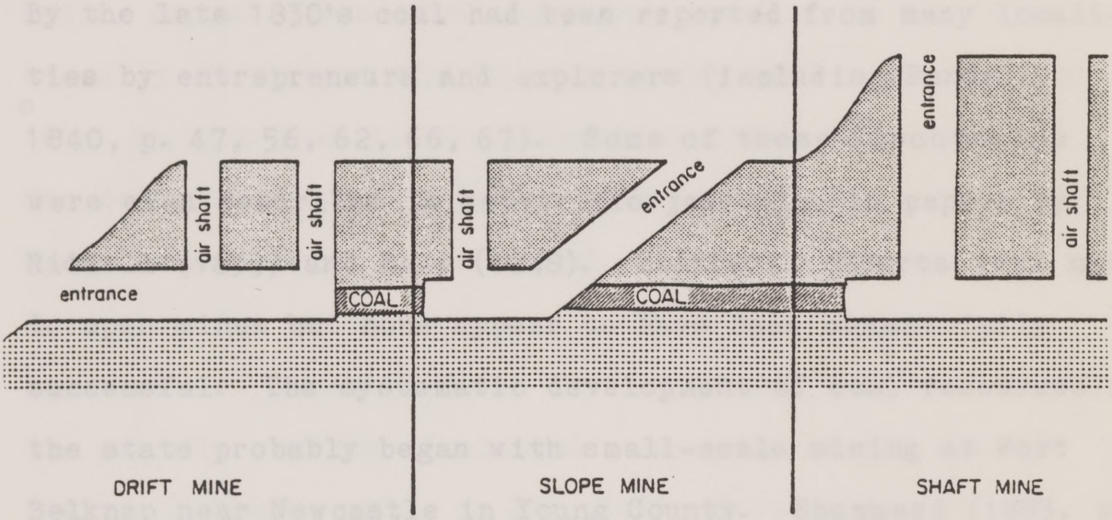


Figure 3. Varieties of underground coal mines in Texas (from Finley and others, 1979, fig. 2, after an original drawing by Caran).

Discoveries and Expanded Use, 1830-1950

Dumble (1892), Phillips and Worrell (1913), Stenzel (1946), Henderson (1964), and Evans (1974) have reviewed the history of coal mining in the state from 1819 to 1954. By the late 1830's coal had been reported from many localities by entrepreneurs and explorers (including Bonnell, 1840, p. 47, 56, 62, 66, 67). Some of these discoveries were even described in scientific journals, in papers by Riddell (1839) and Hale (1848). Scattered efforts were made to open mines but none appear to have been commercially successful. The systematic development of coal resources in the state probably began with small-scale mining at Fort Belknap near Newcastle in Young County. Shummard (1853, p. 182) mentioned the discovery of "Carboniferous" coal near there a short time before. Soldiers from the fort already had excavated a drift mine 20 m (20 yd) into the outcrop by the time Blake (1856, p. 31, 32) visited the site. The significance of this latter report is its connection with the survey for a transcontinental rail line. Railroads provided the means to move coal to market and were the principal consumers of coal in the state until the 1920's (Henderson, 1964, p. 214). For this reason, the vast majority of large and small mines were located immediately adjacent to railroad spur lines. Development of the railroads was a major influence on patterns of settlement and the growth of commerce in Texas, linking suppliers and consumers of coal.

The accessibility of a ready market was the stimulus needed to promote vigorous mining (Henderson, 1964, p. 214). Annual production increased rapidly and fairly steadily throughout the 30-year period that began in 1888 (fig. 4), the year in which the bituminous-coal mines at Thurber in Erath and Palo Pinto Counties began significant operations (Gentry, 1946, p. 9). Accordingly, 1888 was the first year in which there was sufficient mining to permit inclusion of annual records of coal production in Texas in the summary reports of mineral production in the United States (Bullock, 1929, p. 6). Most of the increase after 1888 resulted from the continued development of the bituminous-coal industry although production of lignite almost equalled that of bituminous coal in every year from 1908 to 1918. But in 1919, problems with labor and a depressed market related to competition from oil and gas greatly reduced the output of the largest bituminous coal mines (Gentry, 1946, p. 96-100). This reduction was reflected in the figures for the industry statewide. The production of bituminous coal declined precipitously until the early 1940's when all mines closed (Evans, 1974, p. 1-6). In

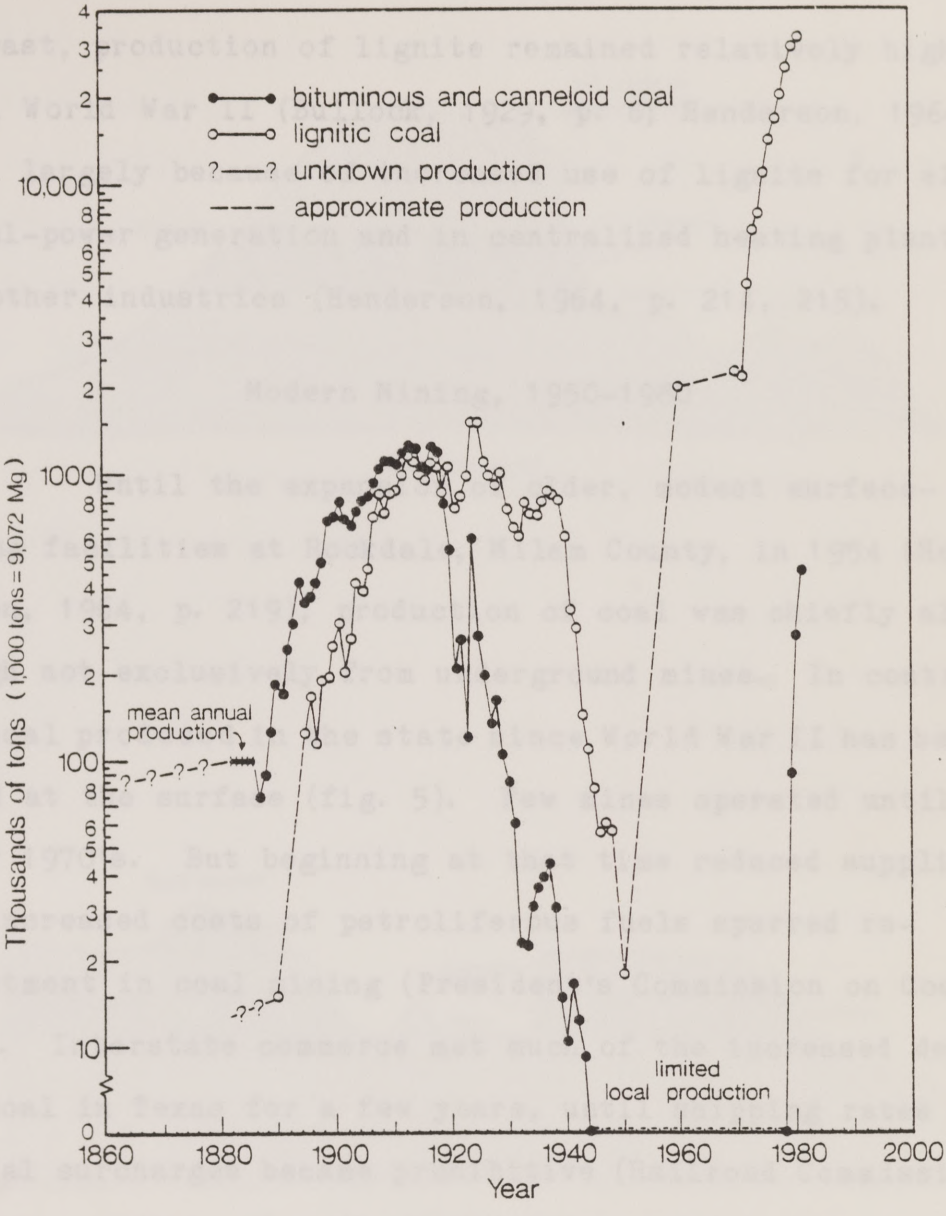


Figure 4. History of production of coal in Texas. Sources of data: A. H. Belo Corporation (1927, p. 255); Bullock (1929, p. 6); Stenzel (1946, p. 205); Fisher (1963, p. 8); Evans (1974, p. 4); Railroad Commission of Texas (1983, p. 9, 10).

contrast, production of lignite remained relatively high until World War II (Bullock, 1929, p. 6; Henderson, 1964, p. 217), largely because of increased use of lignite for electrical-power generation and in centralized heating plants and other industries (Henderson, 1964, p. 214, 215).

Modern Mining, 1950-1980

Until the expansion of older, modest surface-mining facilities at Rockdale, Milam County, in 1954 (Henderson, 1964, p. 219), production of coal was chiefly although not exclusively from underground mines. In contrast, all coal produced in the state since World War II has been mined at the surface (fig. 5). Few mines operated until the early 1970's. But beginning at that time reduced supplies and increased costs of petroliferous fuels spurred reinvestment in coal mining (President's Commission on Coal, 1980). Interstate commerce met much of the increased demand for coal in Texas for a few years, until shipping rates and special surcharges became prohibitive (Railroad Commission of Texas, 1983 p. 1). Since then, intrastate mining has expanded even more rapidly. In Texas production increased from approximately 1.8 million metric tons (2 million tons) in 1970 to 23.6 million metric tons (26 million tons) in 1979 (Kaiser and others, 1980, p. 1). Of special

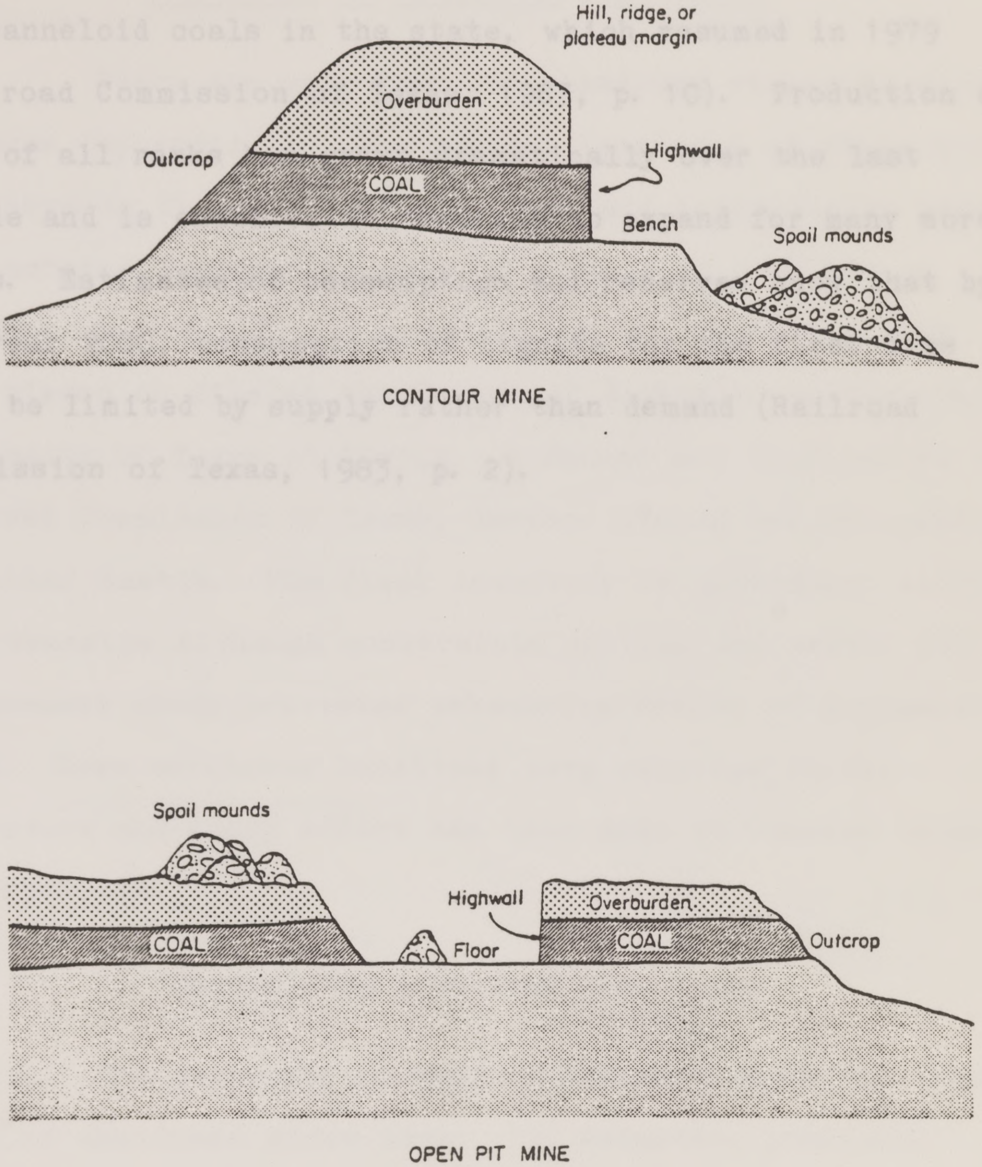


Figure 5. Varieties of surficial coal mines in Texas (from Finley and others, 1979, fig. 4, after an original drawing by Caran).

significance is the mining (at the surface) of bituminous and canneloid coals in the state, which resumed in 1979 (Railroad Commission of Texas, 1983, p. 10). Production of coal of all ranks has grown dramatically over the last decade and is expected to continue to expand for many more years. Estimates of consumption and reserves show that by the year 2000, consumption of lignite for the first time will be limited by supply rather than demand (Railroad Commission of Texas, 1983, p. 2).

INVENTORY OF ABANDONED MINE SITES

There are more than 260 abandoned coal-mine sites in Texas (appendix C). The general locations of these mines are shown in figure 6, and all sites are individually noted on annotated topographic maps at a scale of 1:24,000 or 1:62,500 (appendix B). A complete set of these maps has been placed on file at the Bureau of Economic Geology, The University of Texas at Austin. A second set is filed at the Railroad Commission of Texas, Surface Mining and Reclamation Division, Austin. The final inventory is considered nearly comprehensive although constraints on time and travel for the present study prevented exhaustive review of potential sites. Some erroneous locations were reported in the literature and every effort has been made to resolve these discrepancies.

Recognizing Abandoned Mine Sites

The principal sources of information on the locations of abandoned mines were: (1) selected, published references; (2) unpublished, written and oral accounts of landowners and other residents of the mining areas; and (3) records from several of the companies actively mining coal

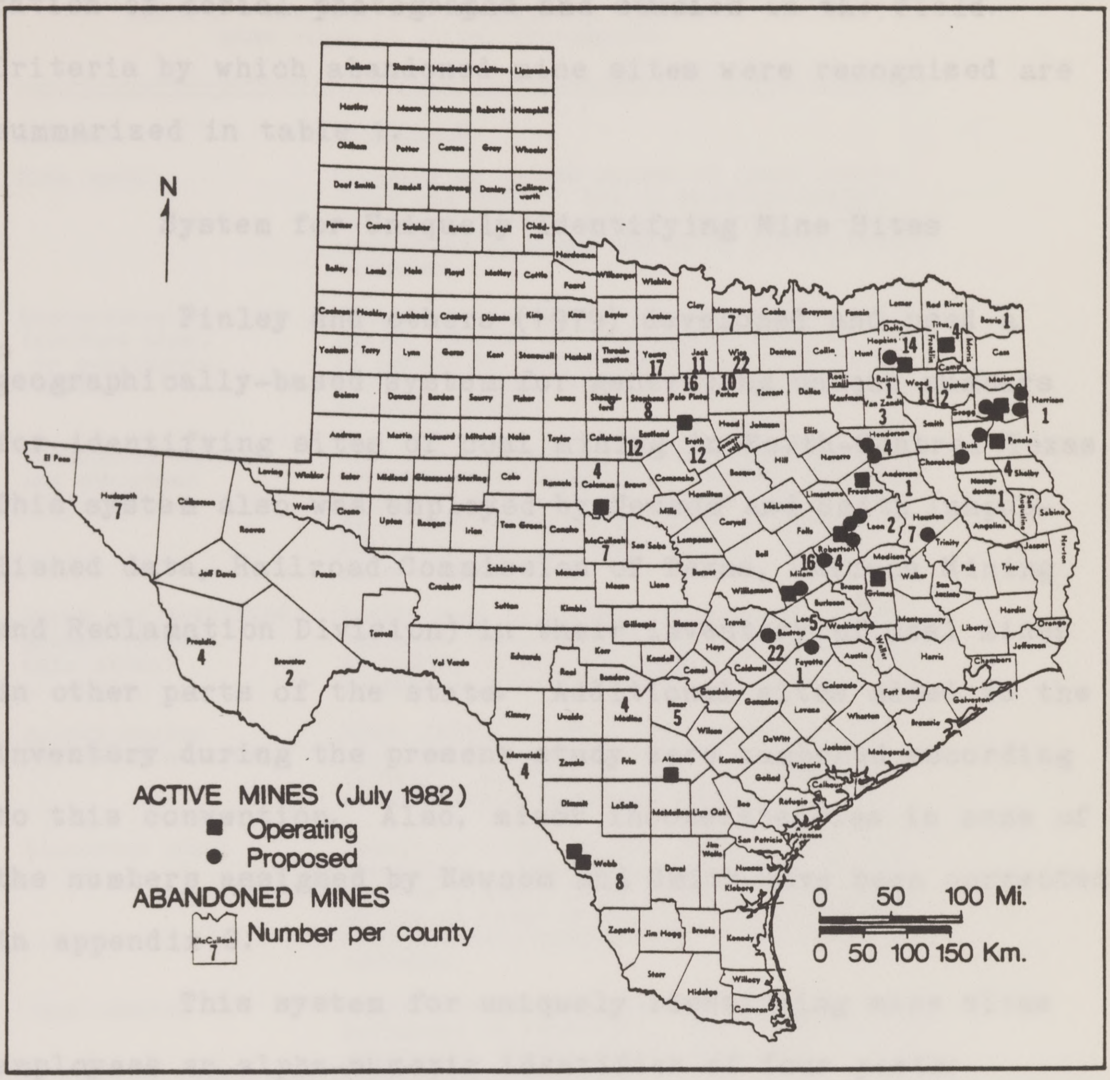


Figure 6. Active and abandoned coal mines in Texas (adapted from Railroad Commission of Texas, 1983, p. 5 and incorporating data from many other sources).

in the state. Other sites were discovered through interpretation of aerial photographs and studies in the field. Criteria by which abandoned mine sites were recognized are summarized in table 1.

System for Uniquely Identifying Mine Sites

Finley and others (1979) developed and used a geographically-based system for generating unique numbers for identifying sites of coal mining in North-Central Texas. This system also was employed by Newsom and Smith (unpublished data, Railroad Commission of Texas, Surface Mining and Reclamation Division) in their inventory of coal mines in other parts of the state. Additional sites added to the inventory during the present study were numbered according to this convention. Also, minor inconsistencies in some of the numbers assigned by Newsom and Smith have been corrected in appendix C.

This system for uniquely identifying mine sites employees an alpha-numeric identifier of four parts:

1. a code of one or two letters identifying the county in which a particular site is located;
2. a code of one, two, or three letters identifying the standard, U.S. Geological Survey topographic map (at a scale of 1:24,000 or 1:62,500) covering the site;

Table 1. Criteria for recognizing abandoned mine sites in aerial photographs

Feature	Appearance
Mine spoil	Circular or linear mounds of loose rubble (rock and soil). Low to moderate relief. Little or no vegetation. Heavily eroded and surrounded by broad sheets of redistributed sediment.
Depressions (surface mines or subsidence basins)	Shallow to steep-walled pits, holes, and low areas, rounded or rectilinear in plan. May be partly or completely filled with water and may be more heavily vegetated than surrounding areas.
Structural debris and equipment	Concrete foundations (slabs or pilings) for structures or equipment. Loading platforms adjacent to roads or railbeds. Retaining walls and narrow-gauge rails on spoil-mounds. Buildings and machinery (rare), probably deteriorated.
Paths and scarified ground (within mine sites)	Trails made by wagons, animals, motorized vehicles (including earthmoving equipment at modern sites). Unvegetated to slightly vegetated, possibly heavily eroded.
Access routes (around mine sites)	Road, trail, or rail spur leading to (or adjacent to) a disturbed area. Narrow (linear), continuous strip of unvegetated to moderately vegetated ground.
Disturbed areas	Smooth to rough, upland surfaces with little vegetation. Generally on a slope, at the base of a hill, or on level ground; rarely on top of ridge or butte. May be heavily eroded and/or buried under redistributed sediment.
Open shafts	Small rectilinear holes at center or around perimeter of mine-site. May be adjacent to structural debris and at the focus of radiating paths.

3. a numeral of one digit identifying the rectangular map-quadrant in which the site is plotted; and
4. a numeral of one or two digits assigned to that site, uniquely identifying it in the sequence of mine sites noted on that topographic map.

For example, the identification number Ea/CN-2-3 refers to a coal-mine site in Eastland County (Ea), within the area covered by the Cisco North (CN) topographic map, in the southwestern (2) quarter of that map-area, and the site was the third (3) to be designated on that map. A key to the codes used to identify counties and topographic maps is provided (appendix B). Map quadrants (1, 2, 3, and 4) are number clockwise from the southeastern corner. During the original investigations for the Railroad Commission, site numbers were assigned to suspected as well as known mines. For this reason the final numeral in the alpha-numeric identifier may be much higher than the number of confirmed mine sites within that map area as the sites are designated in the present inventory (appendix C).

IMMEDIATE IMPACT OF MINING

The immediate effects of coal mining are intrinsically tied to the mining operation itself. Mining necessarily causes environmental changes of various kinds and intensities within a site of finite area. Examples of these unavoidable effects are: removal of vegetation by cutting or uprooting; burial of productive soil through placement of spoil; diversion of surficial drainage into surface mines and around spoil mounds; and disruption of ground-water flow lines along new hydraulic pathways through the mined cavity (surficial or underground). The effects discussed in this section were produced at the time of mining; they are differentiated from delayed effects such as subsidence, erosion, and formation of toxic leachate (discussed separately) which develop gradually. Most of the direct effects of mining dissipate through time, whereas others persist or even intensify.

Agricola (1950, p. 8), in defending mining in the 1550's, conceded that the strongest argument of detractors was that exploitation of minerals caused the destruction of land and water resources. The Strip and Surface Mine Study Policy Committee (1967) of the U. S. Department of the

Interior estimated that surficial mining of coal has disturbed almost 527,000 ha (more than 1.3 million ac) of land in the United States. This figure does not include areas affected by underground mining, and there is no explanation of what constitutes reportable "disturbance." Moreover, the figure almost certainly is an underestimate because the subtotal for the affected area in Texas is substantially low (compare with appendix C).

Affected acreage is directly proportional to the production of coal. Histories of production are readily quantifiable and provide an accurate indication of the chronology of direct impact. Methods employed in mining and the depth and thickness of seams may influence both production and the form and severity of impact. However, the volume of coal mined probably is the best single measure of the intensity of mining and thus the extent of disturbance. Figure 4 summarizes the record of coal production in the state.

Open Shafts, Drifts, and Pits

Coal mining may directly affect the environmental geology of a site in several ways, some of which are discussed by Hrovatic and Sorrell (1973). The first and most obvious effect is the creation of a void, the mine, at the surface or underground. If the mine is abandoned without reclamation the void will remain until it is occluded by natural processes. These processes include subsidence of the overburden, erosion of the walls, and sedimentation. However, several open mine shafts and pits and a few open drifts have been found at sites in various parts of the state (fig. 7). Removal or deterioration of structures at the surface may leave a shaft essentially unmarked, and even slight regrowth of vegetation around the entrance can make detection of the opening very difficult. At least one recent death was caused by a fall into the 120 m (400 ft)-deep shaft of an abandoned cinnabar mine in Brewster County, Texas (James Sansom, personal communication, 1983). Steep highwalls and headwalls of abandoned surface mines also are hazardous to livestock and public safety. They may become unstable, yielding as a mass. An event of this kind too was responsible for a recent, serious injury, at a lignite mine in Hopkins County, Texas (Joe Wallace, personal communication, 1980).

Phreatic Dewatering

Coal is usable as fuel only if it has not been heavily weathered at the surface or within the near-surface zone of aeration above the local water table. Both surficial and underground mining may require excavations below

(a)

(b)

Figure 7. Open mine entrances, Stephens and Eastland Counties, Texas. (a) Drift mine, mine-site number S/CF-1-3, Stephens County, Texas, 1979. (b) Shaft mine, mine-site number Ea/BL-4-2, Eastland County, Texas, 1979.

the depth of the water table. When the mine exceeds this depth, ground water will tend to drain into the opening through the walls. This water then must be pumped from the mine and the water table in the immediate vicinity will be lowered by "dewatering" that part of the aquifer (Cartwright and Hunt, 1981, p. 7-12). This process may reduce, perhaps to zero, the base flow of streams and shallow wells throughout the area in which the water table is depressed.

In Texas lignite is mined from stratigraphic units that also are important aquifers (Henry and Kastning, 1978). In fact, wells must be drilled and pumped on the peripheries of some mines to reduce the inflow during mining (fig. 8). Adverse, local effects on flow rates have been experienced in the past in the arid regions of South, West, and North-Central Texas (unpublished data, Railroad Commission of Texas, Surface Mining and Reclamation Division, Austin). However, the transmissivities of major aquifers are very high in many parts of the state where coal is mined so that effects on water supplies probably are minimal.

Spoil Mounds

Excavation of a mine necessarily produces a large volume of broken rock and soil that has relatively little commercial value and in the past was considered

Figure 8. Water well at mine-site number Hp/SSe-1-2, Hopkins County, Texas, 1980.

waste. This material would now be used in reclaiming the site. But reclamation rarely was attempted until made mandatory in the 1970's. Huge spoil mounds, also called "slack" or "gob" piles, cover thousands of hectares in Texas (fig. 9) and many are more than fifty years old. Johnson and Miller (1979, p. 13) estimated that waste banks (spoil mounds) at coal mines cover almost 72,000 ha (more than 177,000 ac) nationwide, although no acreage is listed for Texas. The irregular, unstable, poorly-drained topography of spoil-covered areas virtually prevents any reuse of these sites without extensive reclamation. Spoil mounds also are major sources of sediment and chemical pollutants that may affect soils, streams, reservoirs, and ground water. Fragments of coal within the mounds can be ignited spontaneously, or by other means, and they may burn for decades, producing noxious or toxic fumes. The fires themselves may cause extensive damage to property and pose a threat to public safety. Such conditions make reclamation of some sites very difficult and extremely expensive, although some reclamation efforts have proven successful (for example, see U.S. Bureau of Mines, 1972). In addition, spoil from coal mines has been used extensively for brick making (Finley and others, 1979, p. 32) and fill material (Joe Wallace, personal communication, 1980).

Figure 9. Oblique aerial photograph of part of abandoned area, mine-site number Mi/Al-3-1, Milam County, Texas, 1981. View is to the southwest. Areas to the left and in the center were mined in 1964, areas above the center and east of the road were mined in 1941, areas to extreme right (middle ground) were mined in 1951.

Mining Structures, Equipment, and Refuse

Other immediate effects associated with mining include erection of structures, installation of equipment, and accumulation of miscellaneous refuse (appendix C). If the site is abandoned these artifacts merely increase the cost and difficulty of reclamation and may constitute a hazard to public health and safety. Structures remain at many of the state's mine sites although most have fallen into ruin and a few may be dangerous. Little equipment is found at these sites, probably because it was easily transported and could be reused or sold. A more common feature is the household garbage and agricultural refuse left at many sites by the miners and subsequent users of the land. This debris can increase the risk of fires and pollution of water, and may be offensive in other ways as well. Some sites, particularly those with open shafts, still are used for disposal of refuse (fig. 10).

Figure 10. Refuse in abandoned and partly collapsed shaft at mine-site number MC/FF-4-3, McCulloch County, Texas, 1979.

SUBSIDENCE

In general, subsidence or earth settling is the process whereby the ground is lowered by gravity in response to changes in the volume or supporting pressure of the substrate. This definition is consistent with that of Bates and Jackson (1980, p. 624) and probably is adequate in most applications. However, the definition obscures or omits some important elements of the process. Dunrud (1976, p. 2) followed the example of some earlier observers and expanded the concept of subsidence resulting from underground coal-mining, to include

> . . . all deformation within . . . the overburden (as well as) at the surface . . . It includes the local upward movement of strata that sometimes occurs above solid-coal mine boundaries or large barrier pillars, which is caused by downwarping of overburden into mine cavities; it also includes the downwarping itself, the associated horizontal tensile and compressive strains produced by strata flexure, and the compressive strain induced by the compression arches.

The term thus applies as well to strains such as floor heave and wall squeeze (upward and lateral flexures, respectively) within the mine and to compressive and tensile strains below and adjacent to the cavity. This expanded concept of subsidence is adopted here, with the following restrictions.

As a practical matter, Dunrud (1976, p. 2) distinguishes subsidence from roof fall which he defines as deformation or movement in the overburden occurring less than two mine heights above the roof. A roof fall occurs simply because the roof is unstable owing to: disturbance from blasting or mechanical mining; preexisting stress in the rock; or inherent weakness. For the purposes of this report collapse of the immediate roof because of instability is not considered subsidence, but no restriction is mandated solely on the basis of an arbitrary height above the mine's roof. Sections of many of the underground mines in Texas, particularly the entries of slope mines, are extremely shallow, in some instances less than two mine heights below the surface. Yet excavations there have induced movements of overburden otherwise identical to those discussed by Dunrud and other investigators, and therefore properly called subsidence.

Quantitative Relations and Prediction of Subsidence

As early as the 1500's, miners were aware of the connection between underground excavation and corresponding movements at the surface (Agricola, 1950, p. 216). Attempts to accurately predict subsidence and deformation are comparatively recent, the earliest reports appearing in Europe in the late 1800's (Dunrud, 1976, p. 3). Since that time knowledge of subsidence has become increasingly sophisticated, and a number of predictive techniques have been proposed. Major works on this subject, in English, are those of Brauner (1973a and b) and the National Coal Board (1965) of Britain. These references also summarize the principal findings of European, South African, Japanese, and American investigators. Important individual contributions to this field of inquiry have been made by Mohr (1956) and Wardell (1953/1954).

Among the oldest and most elementary principles are the "law of the normal" and "law of the vertical." These concepts relate the area of subsidence to the attitude of the coal seam by projecting lines upward through the overburden from the margins of the mine to the surface. The lines are projected either normal or vertical to the plane of the seam regardless of its dip. Predictions on the basis of these simple models may be approximately correct if made with some knowledge of the strength of the overburden. The law of the normal might apply, at least in part, if strata within the overburden are strong, whereas the law of the vertical ordinarily would provide a more accurate representation of subsidence in weak overburden; reasons for this are discussed below. Dunrud (1976, p. 34, figs. 8, 17) found evidence to support both models at mine sites in Colorado and Utah. However, neither law completely accounts for the behavior of the overburden during failure and thus both are unable to predict all displacements and associated stress regimes.

Detailed, topographic profiles across subsidence basins reveal variations in the curvature of the ground. Regions on the curve correspond to zones of differing conditions of stress. These differences correspond both to the magnitude and direction of the stresses below each point on the curve. Figure 11 is an idealized profile of this type. Assumptions inherent in this idealization include: (1) geometric simplicity of the area of extraction (that is, the mine workings); (2) horizontal dip and lateral continuity of the seam, subjacent strata, and strata within the overburden; and (3) attainment of the final topographic profile following all displacements. Also inherent in this model are presumptions of complete extraction of coal from the mine (no residual pillars), absence of backfilled or "gobbed" waste, and attainment of the "critical extraction width," the minimum width that will produce the maximum displacement above a seam of given thickness. These assumptions are consistent with restrictions imposed by Brauner (1973a, p. 2) for derivation of mathematical expressions of subsidence.

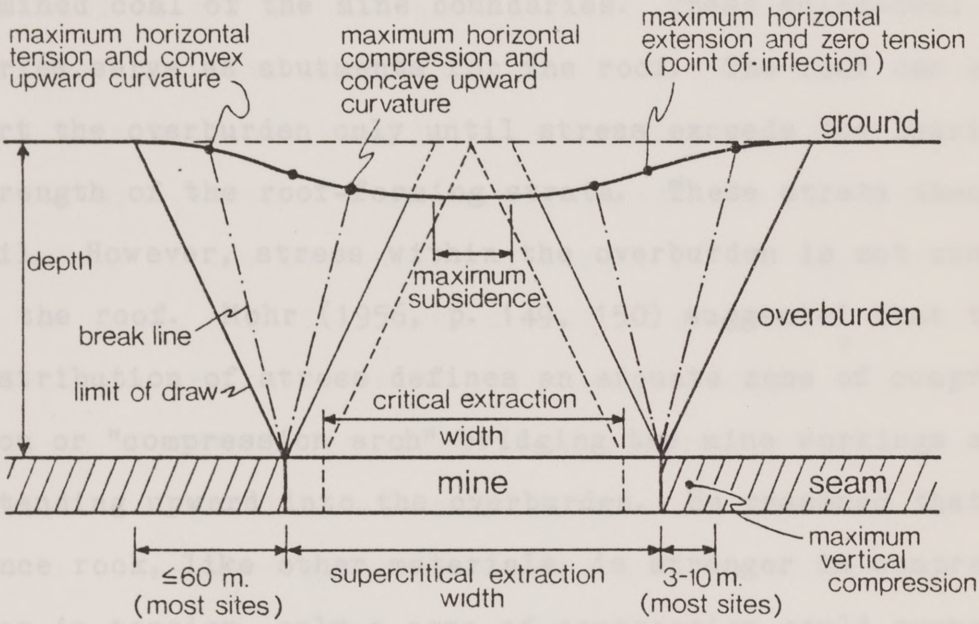


Figure 11. Distribution of stress and strain at an underground mine (after Dunrud, 1976, fig. 2, and incorporating data from Peters, 1978, p. 189, 191).

The disposition of strain and configuration of the surface as shown in figure 11 reveal an important relation between conditions of stress and stratal failure. As mining progresses the load of the overburden is progressively transferred from the area of extraction to the adjacent, unmined coal of the mine boundaries. These solid-coal boundaries serve as abutments for the roof. The roof can support the overburden only until stress exceeds the bearing strength of the roof-forming strata. These strata then fail. However, stress within the overburden is not confined to the roof. Mohr (1956, p. 149, 150) suggested that the distribution of stress defines an arcuate zone of compression or "compression arch" bridging the mine workings and extending upward into the overburden. He reasoned that since rock, like other materials, is stronger in compression than in tension, only a zone of compression could support the overburden. This arching zone becomes broader and higher as the mine is enlarged. Strata beneath the arch gradually collapse or flex downward into the mine, returning some of the load from the mine boundaries, as the arch passes higher into the overburden. The arch may continue to rise, perhaps to the surface, and thereby cause the failure of strata at ground level. But if the width of the mine remains subcritical, or if the stress stabilizes within the overburden, the arch never reaches the surface.

Conditions that either permit or prevent upward migration of the compression arch and other effects can be expressed geomechanically; this is the basis of predictive techniques reviewed by Brauner (1973a and b). But most of the existing methods share two limitations: the simplifying assumptions are unrealistic or unsatisfactory for general applications; and the methods are data intensive. Prediction of subsidence usually is undertaken in planning an active mine. Under these circumstances the thickness and lithology of the overburden, strength of the seam, geometry of the mine, and other data needed to evaluate potential subsidence are known quite accurately, because this information is essential for effectively developing the resource. However, comparable data concerning mines now long abandoned either never were gathered or were not preserved. In most cases is is not possible to determine the residual effects of subsidence at abandoned mines with the precision attainable at active mines. Yet by applying the concepts outlined above a qualitative assessment can be performed with readily available data. An assessment of this type will prove adequate in discussions of subsidence at abandoned coal mines in Texas.

Qualitative Assessment of Subsidence

Underground mining causes subsidence by redistributing the load on a subsurface stratum in such a way that the bearing capacity of the stratum is exceeded. When voids are created by the excavation of coal and rock below ground, the load of the overburden then must be supported by the unconfined strength of the rock within the roof and walls. Redistribution of load in this manner may result in either plastic or brittle failure. Local failure produces an accommodating strain which may be propagated higher in the section through some or all of the overburden, even to the surface. This process may be gradual or essentially instantaneous, and its effects may be localized or widespread.

To a degree, stress tends to dissipate upward through the section, particularly if the bearing strengths of the intervening beds and unmined areas of the coal seam are great. Also, failing strata occupy a greater volume after fracturing. This increase is called the "swell factor." Shrinkage stoping, an efficient method of mining metallic ore, is an application of this phenomenon. A cavity is mined in an ore body and the roof is intensely fractured with explosives. The broken ore falling into the cavity is 20 to 70 percent greater in volume than the unbroken ore (Peters, 1978, p. 187). This excess can be removed and the walls of the mine still will be supported. The roof must be strong enough to span the width of the cavity. In this respect the hard ores differ from coal and its associated strata which are relatively weak and so would collapse and partly recompress the broken rock. However, some volumetric expansion does occur even in coal mines, so that removal of a given volume of coal does not necessarily effect a response of equal magnitude high above the mine level or at the surface. Data from shrinkage stoping define the range of swelling that might be expected within coal mines.

For example, if a seam of coal three meters thick is extracted completely, the ground above might be lowered only one or two meters, or perhaps not at all. The simplest, generalized statement of this relation (modified from Brauner, 1973a, p. 3) is

$$S_{max} = kt$$

where

S_{max} = maximum subsidence

k = the "subsidence factor," an empirical coefficient, and

t = the thickness of the seam if the entire thickness is mined, or the height of the mine workings if not.

The coefficient k is a fraction representing that proportion of the thickness of beds mined out at depth that is not offset by fractural expansion ("swelling") of the collapsed overburden or by the bearing strength of undisturbed strata. Except in very shallow mines swelling is likely to be the more important process. Using data from shrinkage stoping and considering the range in depth of coal mines in Texas, factor k ≐ $(1-f_s)$, where f_s is the swell factor of about 0.2 to 0.7 depending on the type of rock and extent of fracturing. If k were constant, the relation of subsidence to the thickness of mined beds would be linear. But k is a variable because the overburden is heterogeneous and the loss of support affects the strata composing it in a complex, non-linear manner. Clearly, the value of k is related to the strength or bearing capacity and total mass of the strata. Mass is directly proportional to the overburden's thickness which is equal to the depth of the mine. All coal mines in Texas were less than 150m (500 ft) deep, but depths were otherwise variable. The lithology and strength of the overburden at these sites also differ. This diversity is reflected in the observation that subsidence occurred at many but not all of the mines in the state, and the amount of subsidence at various sites ranges over an order of magnitude.

Underground mining routinely causes the roof to begin to settle or collapse during active mining or very soon after coal is extracted. But the time lag between mining and surficial subsidence is inconstant. Wardell (1971, p. 204) postulated that subsidence is complete within two or three years after mining. However, the strain may be delayed until long after the initial disturbance. Dunrud (1976, p. 27, 34) found that significant effects still were being felt six to twelve years after mining ended at one site, and that stresses had remained concentrated above the barrier pillars of another mine for more than 40 years. In North-Central Texas subsidence may be continuing at a few mine sites abandoned 40 to 60 years ago (Finley and others, 1979, p. 30, 31).

Obviously, the pattern and extent of collapse and subsidence at mines vary considerably. Generally they are a function of several interrelated factors:

1. stress in the overburden prior to mining;
2. strength, structure, lithology, and thickness of the overburden;
3. superjacent topography;
4. current land use and composition of surficial materials (for example, deep, cultivated soil or impounded water), some of which may obscure or conceal evidence of subsidence);

5. dip (angle and direction) of the seam relative to its outcrop;
6. strength and thickness of the seam;
7. geometry and chronology of mining;
8. uniformity and completeness of extraction; and
9. time.

These factors affect subsidence in differing ways; general relations are summarized in table 2.

The above nine factors are those that most directly influence mining-induced subsidence and generally are interdependent. For example, the composition of surficial materials in most instances is inextricably linked to topography by cause and effect. Similarly, the state of stress within the overburden is controlled by properties (such as strength, structure, lithology, and thickness) of the overburden. The dip, strength, depth, and thickness of the seam virtually dictate the geometry of the mine, the mining schedule, and the method of mining. Moreover, many factors tend to associate in a reasonably consistent manner throughout a given region, and variations thus are geographically distributed. The most obvious cause of geographic variation in these factors is the distribution of the coal itself.

Distribution of coal in Texas is regionalized by its age and rank: for example, the coal of South and East Texas is Eocene lignite whereas that of North-Central Texas

Table 2. Qualitative relations governing subsidence and deformation of overburden[1]

	S_m = subsidence (magnitude)[2]	S_r = subsidence (rate)[2]	F = deformation (severity of fracturing and folding)[3]
Strength, thickness of overburden	αS_m^{-1} Also, strength α limit angle (ψ) αS_m^{-1} (limit angle defines width of subsidence basin)	αS_r^{-1}	Thickness αF^{-1}. Relation to strength complex: αF^{-1} except locally, at stress concentrations, where strength may be αF.
Composition of surficial materials	Composition influences strength of the material. If material is thick it behaves as does overburden such that strength αS_m^{-1} and αS_r^{-1}.		Exposed bedrock reveals deformation, effects on soil generally are temporary.
Dip of seam relative to its outcrop.	Dip <45°: little or no effect. Dip >45°: αS_m^{-1}	Mining too close to deeply weathered outcrop of coal may result in rapid subsidence.	Dip (even few degrees) toward outcrop: decollement-type or cantilever movements possible.
Strength, thickness of coal seam	Strength of coal in wide barrier pillars (and in mine boundaries if width of mined area < "critical extraction width") is αS_m^{-1}. Thickness αS_m.	Strength αS_r^{-1}. Thickness αS_r.	αF (above margin of mine boundary or wide barrier pillar).

Geometry, chronology of mining	Width of mined area αS_m if width $\geq$ "critical extraction width". Width of barrier pillars αS_m^{-1} unless pillars yield	Width of mined area αS_r. Rate of mining αS_r.	Regularity of geometry αF^{-1}. Width of mined area αF. Width of barrier pillars αF^{-1} (except at margins where αF). Rate of mining αF^{-1}.
Uniformity, completeness of coal extraction	Relation complex, generally αS_m. "Gobbing" or "stowing" may partly compensate for extraction of coal and thus is αS_m^{-1} and αS_r^{-1}.	αS_r	αF^{-1}
Time	αS_m (culumative); S_m eventually becomes a constant.	Generally, αS_r^{-1} (if width of mined area $\geq$ "critical extraction width").	Deformation continues until subsidence is complete.
Preexisting stress; structure and lithology of overburden; topography	Relations complex: may mask, enhance, or retard subsidence and deformation, localize effects, and inhibit prediction of effects. However, irregularities in lithology, structure, or distribution of stress within the overburden, or in the thickness of overburden (beneath topographic breaks) tend to increase deformation. Thus, discontinuity αF.		

Relations summarized or inferred from observations by Briggs (1929, p. 181-184), Mohr (1956, p. 149, 150), Wardell (1971, p. 203-209), Zwartendyk (1971, p. 187-190), Brauner (1973b, p. 23-46), Dunrud (1976, p. 4, 9, 13-38), and Kapp (1976, p. 414-418).

[1] Examples of relations:
$X \alpha Y$: X is directly proportional to Y; an increase in X produces or is associated with an increase of comparable magnitude in Y.
$X \alpha Y^{-1}$: X is inversely proportional to Y; an increase in X produces or is associated with a decrease of corresponding magnitude in Y.

[2] These expressions of magnitude and rate correspond both to the vertical and horizontal components of subsidence. The magnitude of subsidence also affects the horizontal extent of the area of subsidence.

[3] The severity of deformation (fracturing and folding) is an indication of the vertical and horizontal extent of fractures and their associated displacements, the density of fractures, or the size and distribution of folds.

is Pennsylvanian bituminous coal (figs. 1 and 2). Dip of the seams almost everywhere is less than 15 degrees (sites in Hudspeth and Presidio Counties are exceptions), and the strength of the coal generally is related to its rank. Thus, within any region the thickness and depth of the seam prescribe the most efficient method of mining. Underground mining was the only method widely practiced prior to the use of giant, earth-moving equipment for surface mining, principally after World War II. Techniques for extraction employed in the underground mines included (1) longwall advancing, and (2) room-and-pillar retreating. The thickness of the seam determined the choice of technique. Where seams were thin, generally less than 1 m (3 ft), longwall extraction was used. In areas where seams were thick, generally 2 to 5 m (6 to 16 ft), room-and-pillar extraction was favored. Quality of the coal was important, as well. Bituminous and canneloid coals have relatively high heating value and could be profitably mined from thin seams. But lignite, which has a lower heating value usually was mined from very thick seams. Thickness of the seam is one of the principal factors governing the rate and magnitude of subsidence and the severity of associated deformation, and is directly related to the method of extraction.

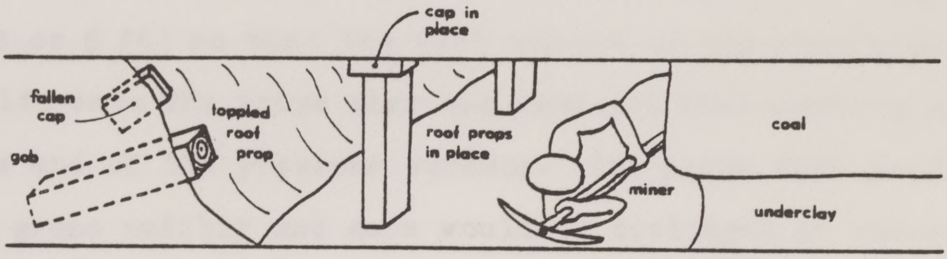
Subsidence and Method of Extraction

Longwall Extraction

Longwall extraction was virtually the only system of mining in use in the underground coal mines of North-Central Texas and western parts of the state. No other method of extraction was practical for mining thin seams where the height of the mine necessarily was restricted to little more than the thickness of the seam except along maintained entries. In such confined spaces even a small flexure of strata forming the roof, walls, or floor would have been prohibitive. The longwall technique reduced or eliminated this problem through rapid and complete extraction, such that the working face continually advanced into unmined areas while the void created by extraction steadily closed behind the miners.

Temporary shoring (props and caps) helped support the roof immediately along the face (longwall), providing a narrow zone that advanced just ahead of the settling roof (fig. 12). Rock and other debris, and waste coal was gobbed into the mined-out areas. Gobbing provided a convenient method for disposing of some of the waste generated in mining but the gob also supported part of the load of the overburden. However, no effort was made to compact the

a



b

Figure 12. Detailed views of longwall extraction in underground mines of Texas.

(a) Historical photograph depicting the working face (longwall) at the end of a main entry in one of the mines at Thurber, Erath County, before 1921. Photograph reproduced courtesy of Texas Highways Magazine from negatives owned by Texas and Pacific Oil Company.

(b) Diagram illustrating the method for extracting coal from the longwall (from Finley and others, 1979, fig. 3, after an original drawing by Caran. This drawing was based on descriptions by former miners who checked the drawing for accuracy).

waste. Thus the density of the gob (relative to the volume of the mined cavity) probably was less than half that of the unmined coal and rock that had occupied that space and fully supported the overburden. The roof was therefore partly unsupported and collapsed within hours or days after mining.

Allard Smith (personal communication, 1979), who had been a coal miner in Jack and Young Counties in the 1920's and '30's, provided a personal account of conditions in the mines. All mining was done by hand or using black-powder explosives, and the rate of advancement was extremely slow by modern standards. But by late afternoon of a typical workday the longwall had been advanced far enough (about 2 m or 6 ft) so that the full weight of the roof began to shift onto the props that had been set that morning and at the end of the previous workday. The props then would begin to groan audibly and soon would be dislodged or violently shattered unless first withdrawn by the miners. These sounds announced the quitting time. By next morning, only a slender crawlway remained along the face of the seam where the unmined coal and nearest props supported a short span of the roof (see also Cummins, 1891, p. 526-529).

Subsidence above longwall mines generally is characterized by rapid, evenly distributed, vertical displacement. Because coal is extracted by advancing the working face, miners remove all of the coal before them along the entire length of the wall, leaving no pillars of unmined coal to support the roof. Subsidence occurs almost immediately and spreads rapidly outward from the main entries as mining continues. The seams are thin so, in general, the vertical strain is small and may be further reduced if the mined-out areas are gobbed. Horizontal strain also is small because the seam is extracted completely and uniformly, leaving no concentration of stress. In fact, Ropski and Lama (1973, p. 118) found that strata 3 to 3.5 times the mine height above the working face of one mine essentially were undeformed, having settled as a unit. Cumulative subsidence reaches a maximum soon after mining is complete, usually within 2 to 3 years according to Wardell (1971, p. 204). Generally there are no further earth movements although local conditions may postpone or prolong the effects. For example, the seam may pinch out or be interrupted by lenses of clastic sediment, which miners call "horses" (Cummins, 1891, p. 530). Irregularities of these kinds can disrupt the geometry of a mine causing stress to concentrate, resulting in local deformation of the overburden or a delay in subsidence.

Room-and-Pillar Extraction

In general, only the thickest seams (2 to 6 m or 6 to 20 ft) are mined by the room-and-pillar technique. Thin seams could not adequately support the overburden unless the pillars were prohibitively large. Therefore, room-and-pillar extraction in Texas was restricted to use in areas where the thickness of seams is greatest, principally in the belts of lignite in East and Central Texas. In the state's single cannel-coal district, in Webb County, the commercial value of canneloid coal permitted a seam only 1 m (3 ft) thick to be mined by room-and-pillar methods (Ashley, 1919, p. 251). To accomplish this the rooms and working entries had to be almost 2 m (5-1/2 to 6 ft) high, so that the pillars incorporated a section of the stratum underlying the coal that was as thick as the seam itself. The cost of handling so much waste relative to the rate of production usually would have made economic mining impossible.

In room-and-pillar mining pillars of coal support the roof while working entries are driven farther off the main entry. When the width of the workings or "panel" begins to put excessive stress on the pillars they are extracted in retreat, that is, from the edges of the panel inward toward the entries. If the entries are driven too far before extraction, the accumulated stress can drive the pillars into an incompetent floor, causing the floor nearby to "heave" or flex upward into the entries. If the floor is strong enough to support the pillar and overburden, or if the pillars are too narrow, the roof or pillars instead may "bump" or burst, sometimes violently. Both heaving and bumping are hazardous and can force abandonment of some reserves, causing the geometry of the mine to become irregular. Unless the abandoned pillars yield under the full weight of the overburden, thereby transferring the load back into collapsed areas within the mine, the stress will tend to concentrate. Normally, stress builds above the unyielding pillars and the margins of barrier pillars and solid-coal boundaries (Dunrud, 1976, p. 34, 35). Such concentrations of stress cause severe deformation of the overburden and possible fracturing, folding, and small local uplifts at the surface. In the early days of mining extraction seldom was complete, frequently no more than 50 percent of reserves, and pillars were not extracted ("drawn") until the entries reached the boundaries of the property (Gentry, 1919, p. 59). Thus, deformation was a common occurrence at most room-and-pillar mines.

A distinctive pattern of subsidence that clearly is related to the geometry of the mine develops above room-and-pillar mines. Coal is extracted primarily in retreat, so the area of greatest subsidence spreads inward from the mine boundaries toward the main entries. Even before extraction of the pillars, the roof above rooms and working entries may begin to settle. If the entire thickness of overburden is affected, the ground above may develop a checkered array of generally undrained depressions (fig. 13). This pattern would be especially prominent if the pillars were not extracted and did not yield, and if the cavities were not gobbed. Because seams mined by room-and-pillar methods generally are thick, the magnitude of vertical displacement can be very significant. At mines in Pennsylvania Earth Satellite Corporation (1975, p. 3) found that depressions caused by subsidence were as much as 5 m (16 ft) deep, and precisely mirrored the workings of underground mines.

Subsidence at Underground Coal Mines in Texas

Subsidence was a common consequence of underground coal mining in Texas as elsewhere. Throughout the United States subsidence may affect an estimated 170,000 ha (418,400 ac) in urban areas, including 325 ha (800 ac) in Texas (Johnson and Miller, 1979, p. 9). These figures probably are conservative because DuMontelle and others (1981, p. 2) stated that more than 300,000 ha (750,000 ac)

Figure 13. Area of subsidence at mine-site number Wd/A-1-2, Wood County, Texas, 1980. Site was reclaimed in 1980. Photograph by Deborah Kocurek, Railroad Commission of Texas (used with permission).

of urban and other lands in Illinois alone had been undermined for coal and therefore were susceptible to subsidence. In Illinois, some areas have remained susceptible even long after mining was curtailed and the land converted to urban uses. The threat of continued subsidence is so severe that a state law was enacted to provide subsidence insurance for homeowners in areas previously mined.

Similar problems did and still may exist in Texas. Phillips (1902, p. 34) reported that extraction of coal had to be curtailed in part of a bituminous-coal mine in Bridgeport, Wise County, ". . . owing to the settling of the ground under the town." Heaving of the floor also was a problem at some mines in Wise County (Scott and Armstrong, 1932, p. 72) and in Webb County, as well (Ashley, 1919, p. 270). Subsidence caused a stream to be diverted into the workings of a mine near Rockdale, Milam County, in 1913, causing the death of one miner (Bullock, 1925, p. 12-14; Betancourt, 1977, p. 91). Similar occurrences, apparently without injuries, were reported from Leon County (Crow, 1938, p. 236, 237). Mining thick seams of lignite often produced ". . . open breaks and deep holes (at the surface), while in other instances the settlement is over large areas, the surface sinking without any great disturbance" (Gentry, 1919, p. 59). Several large areas (4 ha or 10 ac) of subsidence of as much as 3 m (10 ft) still can be seen at mines near Ledbetter, Fayette County. There the seams of lignite are almost 4m (12 ft) thick (Taylor, 1911, p. 8). Virtually all sites of underground coal mining in the state have experienced localized subsidence over mined-out areas and shallow entryways. In fact, subsidence was such a common occurrence that it was relied upon to provide some of the airways for ventilating at least one mine in Milam County (Phillips, 1902, p. 10).

The most common example of subsidence at underground coal mines in Texas is collapse of the entrance portal of a slope or drift mine. Few abandoned mines in the state remain open to their interiors, with the small drift mine, number S/CF-1-3 in Stephens County (fig. 6a), being an exception; however, many shafts are at least partly open. There are numerous references in the literature concerning the failure and instability of mine openings soon after cessation of mining. Unless the entrance is maintained or protected in some other way, even the thinnest overburden begins to collapse as soon as the shoring (usually wooden timbers) at the portal succumbs to exposure, erosion, or scavenging. Reuseable materials, including the shoring, were methodically removed when most mines were abandoned (Gentry, 1946, p. 201; and Betancourt, 1977, p. 97). This resulted in almost immediate collapse. Without the artificial support from timbers, props, or columns of rock, the overburden simply was unable to maintain an open span across an access portal, possibly because beds near the entrance were weathered and presumably weakened. In addition, the roof was higher in the entryway than in the workings. Thus the subsidence that follows abandonment of a slope or drift mine probably progresses from the portal inward along the main entries. Observations in the field support this hypothesis because the magnitude of subsidence decreases from a maximum at the portal of some mines in southern Coleman, Jack, Young, and Wise (east of Bridgeport) Counties. There is little relief or slope at any of these sites and the areas of subsidence form narrow troughs. Where mines opened onto steep slopes, as at some sites in Montague County, colluvium and slumped debris generally filled the portals. A few mines may have been closed intentionally, over concern for safety or other reasons. But most operators probably intended to resume mining and so were unlikely to deliberately seal their mines.

Some long-abandoned mines may be undergoing active subsidence. Upland mine sites in southern Coleman and northern McCulloch Counties are marked by small (less than 5 m or 16 ft in diameter, 1 m or 3 ft in depth), mostly circular subsidence pits and basins and open fractures at the surface. The walls of the pits are nearly vertical to upwardly convex and virtually free of vegetation, but clearly are not the product of erosion alone. These features are unmistakable evidence of recent movements of the ground in an area where mining ceased more than 60 years ago (Linnie Box and Samuel Hays, personal communication, 1979; Finley and others, 1979, p. 75, 137). Overburden is relatively thin at these sites; as a result all subsidence should have occurred long ago. But the mines were small with narrow longwalls, and the indurated sandstone or limestone of the roof was strong. The small size of the mines, the strength of strata composing the roof, and the thin overburden may have preserved cavities within the mines or otherwise delayed the upward propagation of stress. Why the ground at several sites is being affected simultaneously is unclear. A recent renewal of interest in coal in this area has prompted extensive drilling and other exploratory efforts by several companies. One of these, Amistad Mining Company, opened a surface mine near Rockwood, Coleman County, in 1979. Mining requires the movement of heavy trucks and drilling machinery near some of the abandoned workings, and the use of explosives (Joe Williams, Sr., personal communication, 1979). Perhaps these activities produced strong vibrations or other disturbances that could have caused the sudden increase in subsidence. However, a different mechanism for inducing movements almost certainly has been responsible for recent subsidence at other sites and may have affected those of Coleman and McCulloch Counties, as well.

Water infiltrates through the fractured and downwarped strata above mines. This movement of water carries fine-grained sediment and even coarse rubble from the fractured zone deep into some of these mines. The loss of sediment can be so great that it permits continued subsidence of the near-surface strata. In this way the change in elevation at the surface actually may exceed the maximum displacement immediately traceable to mining. That is, vertical displacement may be greater than the height of the mined-out area. In fact, a conduit could develop that would extend from the surface through the entire thickness of the overburden to openings below. An event of this type occurred in Virginia following a deluge resulting from Hurricane Camille in 1969 (Doehring and Vierbuchen, 1971). Passages within a cave were flushed and enlarged as water poured through these openings. New sinkholes were created where the roof of the cave was no longer supported and locally collapsed. At mine sites in Texas the process involves redistribution of supporting sediment, effectively enlarging the residual cavity. This appears to be an important contributing cause of rapid, "pit-type" subsidence in urban areas that have developed above abandoned coal mines in Illinois (DuMontelle and others, 1981, p. 10-12). If such an area had subsided previously due to extraction of coal there very likely would be a depression that would tend to funnel runoff into the collapsed strata, flushing sediment into preserved voids within the mine. Small, steep-walled pits are common in broad, upwardly concave subsidence basins at mine sites near Como, Hopkins County. One pit was 5 m (16 ft) deep but was filled by a local farmer (Deborah Kocurek, personal communication, 1981; and unpublished data, Texas Railroad Commission, Division of Surface Mining and Reclamation, Austin).

An unusual example of recent, surficial displacement above historic underground mines in Texas involved two mines at Lake Cisco in Eastland County (Finley and others, 1979, p. 30). When this large artificial reservoir reaches its capacity, the two small shaft mines are completely inundated. During the summer of 1979 the lake quickly rose above the entrances to these mines following a heavy rainstorm, then dropped to its normal position. The movement of water into the zone of subsidence, coupled with the pumping action caused by the rapid rise and fall of the water table, apparently caused a sudden collapse of the surface. The resulting depressions were sharply defined and cylindrical or bell-shaped in cross section. Each feature was approximately 1.6 m (5 ft) deep and both expanded downward from circular openings 0.5 m (1.5 ft) and 4 m (13 ft) in diameter.

An area of 2 ha (5 ac) subsided at least 1 m (3 ft) at a mine site (W/BW-4-7) north of the brick plant in Bridgeport, Wise County (Finley and others, 1979, p. 28, 30, 235-237). The rectilinear boundaries of the subsidence basins within this area were sharply defined when the site was photographed from the air in 1967 (fig. 14). Since that time, the site has been covered with solid waste from the brick plant. The basins developed beneath an intermittent stream. Young woody plants line the edges of the basins which are seasonally filled with runoff. The precise definition of the basins' boundaries, and the apparent absence of sedimentary deposits and mature vegetation suggest that subsidence occurred not long before the site was photographed. This hypothesis cannot now be independently confirmed, but is consistent with observations at other sites of comparatively recent subsidence.

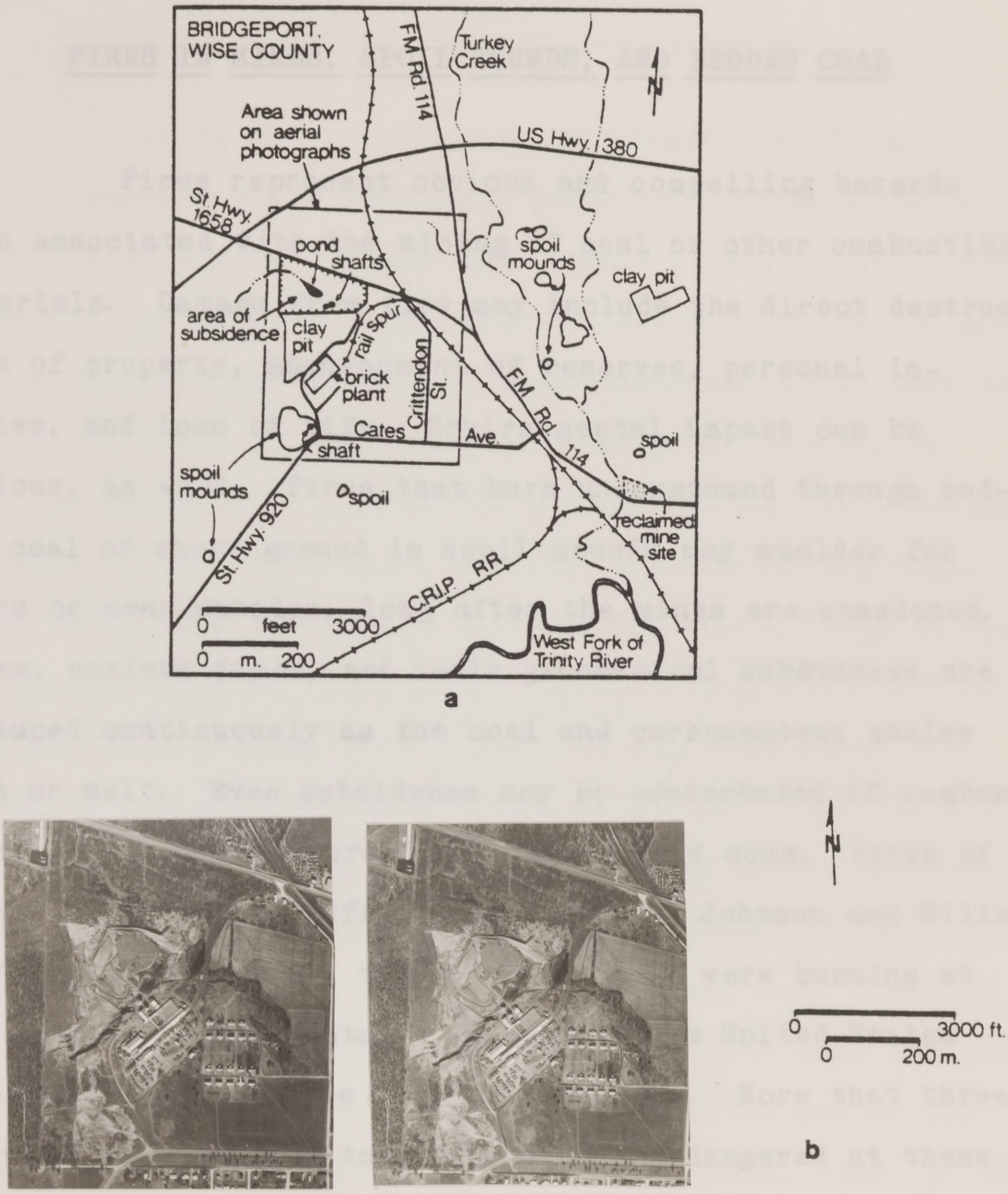


Figure 14.

(a) Area of subsidence in Bridgeport, Wise County, Texas.

(b) Stereogram of site (January 12, 1967; vertical aerial photographs, frames 119 and 120, U.S. Department of Agriculture).

FIRES IN MINES, SPOIL MOUNDS, AND BEDDED COAL

Fires represent obvious and compelling hazards when associated with the mining of coal or other combustible materials. Damage from fire may include the direct destruction of property, abandonment of reserves, personal injuries, and loss of life. Environmental impact can be serious, as well. Fires that burn underground through bedded coal or above ground in spoil mounds may smolder for years or even decades, long after the mines are abandoned. Smoke, noxious fumes, and toxic geochemical substances are produced continuously as the coal and carbonaceous shales burn or melt. Even subsidence may be exacerbated if combustion spreads widely through an underground seam. Fires of this type are very difficult to control. Johnson and Miller (1979, p. 19) reported that in 1978 fires were burning at 261 coal mines in 16 states throughout the United States including one incidence reported in Texas. More that three-quarters of a billion tons of coal are endangered at these sites.

Fires Resulting from Mining Practices

Before the introduction of comparatively modern safety measures there were many potential causes of fires in mines. More than a century ago, Chance (1883, p. 417, 418) discussed the extreme difficulty of interpreting the origin of any fire, at either an active or abandoned mine, that had not been witnessed. For example, underground mining in Texas formerly necessitated the use of candles, oil-burning lanterns, and carbide lamps for lighting and furnace-type draft ventilators (Taylor, 1911, p. 5; Gentry, 1919, p. 59; Sloane and Sloane, 1970, p. 79, 99). Above ground, but in the immediate proximity of mines, boilers were fired continuously for steam-powered hoisting (Broman, 1915, table following p. 24). These types of equipment almost certainly were responsible for some fires or explosions in Texas although there are few reports in which they were named as cause. An exception was the very serious fire that occurred in the tipple (fig. 15) over the main shaft of one of the Thurber mines in Erath County, in 1897 (Gentry, 1946, p. 36-40). This fire was attributed to the careless placement of a torch used for lighting. The mine was heavily damaged and miners were injured but the fire did not spread into the seam.

Figure 15. Tipple at mine site in Thurber, Erath County, Texas, about 1910. Mine was named "The Colonel." Wooden props stacked at left. (Photograph reproduced courtesy of Texas Highways Magazine, from negatives owned by Texas and Pacific Oil Company).

In the larger mines electricity was introduced for lighting, hauling, and ventilating, especially after 1900 (Broman, 1915, table following p. 24). Records of accidents that were complied by the State Inspectors of Mines provide no data regarding electrical mishaps other than noting that two fatalities had resulted from electrocution or burns between 1909 and 1928 (Bullock, 1929, p. 3, 4). But undoubtedly there were numerous, unreported, minor incidents. Coal-cutting machinery came into limited use in Texas (Broman, 1915, table following p. 24), and even as late as the 1970's this type of equipment could produce sufficient frictional heat to ignite coal dust or methane (Furno, 1978, p. 3, 4). Black-powder and other explosives were in use in many mines by the early 1900's and became increasingly common in the next two decades (Broman, 1915, table following p. 24; Bullock, 1929, p. 4). Each of these devices or products was a potential cause of fires in mines, particularly if associated with local concentrations of methane, hydrogen sulfide, or suspended coal dust.

Gentry (1919, p. 59) reported that concentrations of methane were ". . . never encountered in the lignite mines of Texas." In his annual report as the State Inspector of Mines Gentry (1922, p. 4) extended this conviction by stating that "The bituminous and lignite seams of Texas are practically free from gas. Gas and dust explosions have been unknown in Texas mines." Mine Inspector Bullock (1925, p. 4; 1929, p. 7) offered an identical assessment of the situation. However, Taylor (1911, p. 23), the first State Mine Inspector, earlier had reported three incidents of gas explosions, one in a mine at Thurber, Erath County, and two in mines near Eagle Pass, Maverick County. All three incidents involved serious, but non-fatal injuries to a total of five miners. In addition, Browman (1915, p. 11-13) noted a fatality resulting from burns from a gas fire in a mine at Dolores, Webb County, in 1914. Curiously, this accident was included, and its cause identified, in statistical summaries in the reports of both Gentry (1922, p. 8, 9) and Bullock (1925, p. 7, 8; 1929, p. 3, 4), although other statements by these authors denied occurrences of this type. It is now clear that gas was present in some mines and was a cause of fires.

Other fires that apparently did not involve gas were reported, as well. Both Gentry (1922, p. 8, 9) and Bullock (1925, p. 7, 8; 1929, p. 3, 4) recorded four fatalities in 1918 caused by fires of undisclosed origin that occurred at an unnamed mine or mines. Taylor (1911, p. 9) indicated that the Watelsky Mine in Hopkins county was on fire at the time of his inspection. Almost three months later the fire was still burning but had been contained, and work on the mine was continuing. Broman (1915, p. 10) noted with evident pride that a troublesome fire at a mine in Young County had been controlled during his administration as State Mine Inspector:

> With the closing down of mine No. 2 at New Castle the most difficult thermogenic problem that has ever existed in the coal fields of Texas was solved. It was an interesting but very hot problem while it lasted.

Although serious fires and explosions were not common, Bullock (1929, p. 24-37) urged the establishment of stringent preventive measures.

Even after abandonment of a mine there was a continuing risk of fire. Mines with open shafts commonly were used as sites for disposal of refuse (Finley and others, 1979, p. 31-33). Agricultural, domestic, and industrial wastes still fill some shafts and subsidence pits (fig. 10). The wastes themselves could ignite accidentally or even spontaneously, or might be burned intentionally to eliminate odors and vermin. Fires could spread through spoil and bedded coal, although there are no records of such occurrences.

It is important to note that after issuance of the mine inspector's report for 1910 (Taylor, 1911) only those fires and explosions that resulted in serious injuries or loss of life were noted in annual reports of the State

Inspectors of Mines. In addition, Bullock's (1925, p. 3) remarks indicate that before 1924 activities and accidents in small mines were not covered in these reports. Whether there were other fires that went unreported is unknown but probable. Only a few of the mine inspectors' reports are now accessible through archives and libraries; other records either never were published or have not been preserved. The reports are the primary source of data on coal mining in the state during the historic period of most active mining.

Fires Occurring Naturally

Most of the fires in seams and spoil mounds in Texas resulted from natural causes. Two natural phenomena could readily kindle fires in exposed coal or mounds: lightning and spontaneous combustion.

Lightning

Lightning causes fires by striking the ground, trees, or other objects and igniting combustible materials. Lightning damage is an important factor in sylvaculture and other susceptible industries (Komarek, 1966). At mine sites, above-ground structures such as tipples, hoisting engines, and storage buildings could be struck. The electric current might then be conducted into a seam or spoil mound, or the bolt could ignite a fire elsewhere and it would spread into the coal or spoil.

Lightning is cited as a possible cause of fires in coal seams by many authors including Rogers (1917, p. 1) and Lonsdale and Crawford (1928, p. 153). However, such occurrences probably are rare. The conditions needed to initiate and sustain a significant burn in bedded coal are specific and ephemeral. Also, coal tends to weather recessively and does not produce topographic prominences that might concentrate electrical charges. To cause a fire in bedded coal lightning would have to strike within or near the outcrop of a seam at a site where the coal was suitable for combustion. Stratigraphic continuity, minimal moisture, and adequate aeration of the seam are necessary for a burn to begin and propagate from the point of ignition. The probability that all conditions would be met simultaneously throughout a large part of the seam near the point of conduction of lightning is extremely low. Repeated strikes of lightning, at several points along the outcrop, might be required to initiate an extensive burn by this means. There is a much greater probability that lightning could cause a large fire in vegetative groundcover or man-made structures and thereby ignite a seam across a broad area of its outcrop or near-surface subcrop, yet even this scenario is unlikely.

Similarly, ignition of spoil by lightning would be an infrequent event, although there has been at least one occurrence of this type in Texas. A wooden tipple at an abandoned mine near Terlingua, Brewster County, was struck by lightning in the summer of 1981 (James Sansom, personal communication, 1983; unpublished data, Railroad Commission of Texas, Surface Mining and Reclamation Division, Austin). The resulting fire ignited flammable spoil and continues to burn even now.

Spontaneous Combustion

By far the most common natural cause of fires in coal is spontaneous combustion. Spontaneous combustion results from slow oxidation of coal and associated sulfide minerals under favorable conditions.

Coal is subject to oxidation wherever: (1) it is stockpiled within mines or at the surface; (2) seams are exposed in outcrops and mines; (3) fine particles of coal are concentrated in spoil mounds. Oxidation is an exothermic reaction. Heat evolved in this process can accumulate if the oxidizing material is insulated so that the heat is retained. If the temperature of the oxidized material reaches its kindling temperature combustion may occur.

Oxidation proceeds at a rate dependent on the supply of oxidants, principally atmospheric oxygen. The reaction is aided by an increase in the surficial area of the material. Weathering "slacks" or disaggregates the coal into fine particles. Powdery coal is rapidly oxidized producing a great quantity of heat. Oxidation of accessory minerals such as pyrite or marcasite may occur simultaneously, contributing additional heat. The general reactions and related "heats of formation" (H_f^o) of the oxidation products are:

$C(s, \text{ in coal}) + O_2(g) \longrightarrow CO_2(g)$,

$H_f^o\ (CO_2) = -94{,}052$ cal

$4FeS_2\ (s, \text{ pyrite}) + 11\ O_2(g) \longrightarrow 2\ Fe_2O_3(s) + 8\ SO_2(g)$

$H_f^o(\text{reaction}) = 2\ H_f^o\ (Fe_2O_3) + 8\ H_f^o(SO_2) - 4\ H_f^o\ (FeS_2)$

$= 2\ (-196{,}500) + 8(-70{,}960) - 4(-42{,}520)$ cal

$= -790{,}600$ cal

The combined enthalpy of these reactions is -884,652 cal and the negative sign indicates the reaction is exothermic. This is a large net increase in heat even though the oxidation of pyrite may be relatively slow.

Carbon and ferrous sulfide are not the only oxidizable materials within the coal. Hydrogen also is available, in appreciable quantities, as are methane and carbon monoxide. These gases are produced by the gasification or "dry distillation" of coal, at temperatures as low at 300°C (570°F), and they too oxidize exothermically (Phillips and Worrell, 1913, p. 50; Edgar, 1978, p. 135). However, other substances also are present so that not all of the heat generated in this manner is conserved. Water, nitrogen (in the air and from gasification of the coal), and carbon dioxide absorb heat which then is removed convectively. Some of the heat is absorbed by the surrounding rock material and radiated to the atmosphere.

Heat that does accumulate raises the temperature of the coal and rock. Church and others (1979, p. 1883), citing unpublished industrial data, state that loosely piled coal may ignite at a temperature of only 80°C (176°F), but this figure must represent the temperature of the exterior of the pile at ignition, not the temperature at the core. Under laboratory conditions, sulfur in organic complexes and elemental form would ignite at the lowest temperature of any of the materials present, at about 243°C (470°F) (Anonymous, 1916, p. 448). Combustion of sulfur causes further elevation of temperature, but the increase is slight under these conditions because this "free" sulfur is a relatively minor constituent. Most of the evolved heat is produced by combustion of other substances. Ignition of canneloid and bituminous coals occurs in air at 353°C (668°F) and 408°C

(766°F), respectively, followed by hydrogen at 555 to 610°C (1,031 to 1,130°F), methane at 650°C (1,202°F), and carbon monoxide at 650 to 700°C (1,202 to 1,292°F). As each constituent is oxidized it produces additional heat. However, the supply of air may become a limiting factor before these temperatures are reached.

The "completeness" of combustion controls the temperatures attained when carbon burns. If combustion is complete, such that all of the carbon is converted into carbon dioxide, the temperature may reach 2,681°C (4,858°F) (Anonymous, 1916, p. 449). If combustion is incomplete, as when the supply of air is deficient, carbon monoxide is formed as an additional product, and the evolved temperature decreases as the percentage of carbon monoxide increases (at the expense of carbon dioxide). If the supply of air is only half that required for complete conversion of carbon to its dioxide, all of the carbon instead is converted to carbon monoxide and the temperature of combustion is 1,506°C (2,743°F).

The temperatures of underground fires or "burns" probably fall in this latter range although there virtually is no data from direct observations. Church and others (1979, p. 1883) stated that combustion of loosely stacked coal can generate temperatures of more than 1,400°C

(2,550°F). Raimondi and others (1975, p. 38) estimated the temperature generated in a burning seam at a depth of 33 m (107 ft) during a field test of in situ gasification in Kentucky. They concluded that the temperature in the zone of combustion had reached 1,370 to 1,650°C (2,500 to 3,000°F). Combustion evidently was incomplete because much of the coal had carbonized to coke, rather than gasified. This occurs when the supply of air is restricted and carbon is converted to its monoxide. The temperature estimated by Raimondi and others is consistent with that of incomplete combustion of carbon under laboratory conditions as cited above. No other estimates or measurements of the temperatures developed in underground fires of this type were found in the literature reviewed during the course of my study. I outline a new method for inferring the temperature of a burn later in this report.

Fires in Spoil Mounds

The most common sites of fires or flameless combustion at mines in Texas were stockpiles of coal and spoil mounds containing fragmented rock mixed with undersized, unmarketable particles of coal. Theophrastus (as cited in translators' footnote 15, Agricola, 1950, p. 34, 35, 607) described such burns at mines and other exposures in Greece and Sicily almost 2,300 years ago and clearly identified the cause as spontaneous combustion. Cancrinus (1980, p. 127: paragraph 558), writing in the late 1700's, described the heat produced in bedded coal and pyritic matrix "through access of air and water." Coal did not come into widespread use in most of Europe until much later (Chance, 1883, p. 2-4). Yet the commentaries by Theophrastus and Cancrinus prove that even at an early date, factors causing spontaneous combustion were well known.

Most spoil mounds contain at least some fire-hardened rocks or "clinkers" produced by combustion. Miners generally referred to this material as "red dog" because of its dark-red color imparted by the predominance of ferric iron resulting from oxidation (Thrush and others, 1968, p. 904; Hrovatic and Sorrell, 1973, p. 514). Some mounds consist of little else. This material is so common at mine sites in Texas that it is a useful bulk commodity in its own right, serving as aggregate surfacing for small roads, rail beds, parking areas, and athletic tracks (Ashley, 1919, p. 270; Hrovatic and Sorrell, 1973, p. 514; Randy Bennet, personal communication, 1979). Clinker was even produced artificially in shallow pits for use as railroad ballast (Fett, 1969, p. 13-21). Mine wastes including clinker were used extensively in brick making at Thurber in Erath County

(Gentry, 1946, p. 36) and at Bridgeport in Wise County (Scott and Armstrong, 1932, p. 68). In fact, spoil is again being recovered, to be made into bricks and cinder blocks at manufacturing plants in Bridgeport and at Lyra in Palo Pinto County. The shalely spoil is considered an ideal material for this purpose.

Spoil mounds provide virtually ideal conditions for spontaneous combustion. Fuel, consisting of particles of coal and carbonaceous shale, is concentrated in a porous medium that allows penetration of air. Much of the fuel is insulated within the interior of the mound where heat can accumulate. Compaction of the mound, owing to loading and cohesion of moistened particles, further concentrates the oxidizing fuel. Variations in the moisture content of the mound facilitate packing when wet and ignition when desicated. In addition, sulfide minerals may be abundant and are capable of generating considerable heat when oxidized. As a result burns in spoil mounds were common. Ashley (1919, p. 270) noted that spontaneous combustion, owing to oxidation of pyrite, had occurred in the large mounds produced from mining thin beds of canneloid coal in Webb County. Similar conditions developed in mounds at mine sites in Leon County (Crow, 1938, p. 235) and most other mines in the state. Some of these burns were long lived.

Randy Bennet (personal communication, 1979) reported that as recently as the late 1960's or early 1970's, combustion was continuing within mounds near Thurber, in Erath and Palo Pinto Counties. Forty or more years after the spoil was mined snow would melt immediately after falling on the mounds and low flames could still be seen at night on some of them. All mine wastes at these sites were disposed between 1886 and 1921 (Gentry, 1946, p. 6 and 40).

Fires in Unmined Seams

Fires also occurred within seams, beginning at the outcrop then spreading underground. Most of the fires began naturally. A few others may have resulted from accidents, although no occurrence of this kind has been documented. Haley (1929, p. 25, 26) identified human carelessness in everyday activities as the principal cause of extensive grass fires in the southern Great Plains in the late 1800's and early 1900's. Farmers and ranchers of that period customarily used fire for clearing land for agriculture. Such fires could have ignited exposed seams. Some groups of American Indians, including populations in Texas, also set grass and brush fires for hunting, warfare, range management, and ceremonial purposes (Roemer, 1849, p. 191; Pope, 1856, p. 61; and Barrett, 1980). In a few areas at least, Indians were aware of coal's combustible qualities at the time of European contact. Presumably this knowledge came from witnessing fires ignited at the outcrop either accidentally or by natural processes.

Spontaneous burns have caused many underground fires in bedded coal. Such fires are known from historic records and from evidence of combustion residues in Texas and elsewhere. Buckley (1874, p. 24, 25) reported an incident of this kind in northern Milam County, Texas, in 1867. He had visited a site along the Brazos River and found beds of Eocene Wilcox lignite of which an incomplete section 5 to 8 m (15 to 25 ft) thick was exposed in the bed of the river. Upon returning to the site several years later, Buckley found the seam on fire, and learned from local residents that the coal had been burning for two years. Fire had penetrated so deeply that although the river repeatedly had submerged the entire outcrop, combustion was continuing unabated. This was causing the overburden to slump into a burned-out void. Buckley thought the fire might have been contained or extinguished by the local populace during these floods had anyone made an effort. The cause of the fire is unreported but probably is attributable to spontaneous combustion. Similar occurrences were reported from Leon County (Crow, 1938, p. 235).

Lonsdale and Crawford (1928, p. 147-149) investigated the area of an extensive, spontaneous burn (probably Pleistocene) in southernmost Freestone County, Texas, 3.3 km (2 mi) east of Donnie, after samples from the site were submitted to the Bureau of Economic Geology for identification. The samples resembled fragments of vesicular, igneous rock ("basaltic lava," p. 147). Rocks of this type would have been anomalous in the Tertiary section of East Texas. Lonsdale and Crawford visited and mapped the site and collected additional specimens. The samples were found to be a "pseudo-igneous," natural slag (clinker) formed by the partial fusion and recrystallization of terrigenous rocks. The rocks had been interbedded with a seam of lignite that had burned in place. Lignite of the Eocene Calvert Bluff Formation, Wilcox Group, crops out discontinuously at this locality over an area 3.3 km (2 mi) long (along the northeastward strike) and 0.8 km (0.5 mi) wide (along the southeastward dip). The lignite was protected from rapid weathering by an overlying bed of massive, indurated sandstone (p. 149). Combustion of this lignite began along its limited, hillside outcrop and spread deep into the seam, melting the contiguous and intercalated beds of sandstone and shale. Upon cooling the melt formed various solid phases ranging from glass to a phenocrystic, ophitic material comprised of pyroxenes, magnetite, and euhedral laths of plagioclase in order of generally decreasing abundance (p. 154-158 and plates). Flow structures were well developed in some pieces. The entire burned zone was 3 m (10 ft) in aggregate thickness and consisted of pseudo-igneous rock, baked shale, and sooty cinders of lignite. Rock that was least affected by heat showed no sign of fusion or recrystallization, but was discolored, having turned bright red as ferrous iron was oxidized to ferric oxide. As the lignite was consumed the brittle, pyrogenic materials were broken and disoriented by slumping, producing irregular bedding. The lateral extent of the zone of combustion was well defined in some exposures as the contact between sooty, deteriorated lignite and the fresh, undisturbed seam (p. 150).

Lonsdale and Crawford (1928, p. 148) referred to this occurrence as the first of its type to be reported in Texas, but noted similar occurrences throughout the north-central part of the United States, notably in Montana, Wyoming, and the Dakotas (see also Rogers, 1917, and other references cited by Lonsdale and Crawford, 1928, p. 148). However, Hill (1889, p. 298) previously mentioned that massive igneous rock had been reported from Yegua Knobs, a group of local prominences in Lee County. (Note: Hill gave the location as Bastrop County but the Knobs are in fact just across the county line in Lee County.) Yegua Knobs lie along the line of contact of the Eocene Calvert Bluff and overlying Carrizo Formations as mapped by Barnes (1981). I briefly visited the Knobs in 1981 in connection with a study of Late Cretaceous volcanism in South and Central Texas (with T. E. Ewing, report in preparation), to investigate Hill's suggestion of igneous activity in the area. The stratigraphy of the site precludes an occurrence of igneous rocks of the type known elsewhere in the region. I encountered no rocks resembling those described by either Hill (1889) or Lonsdale and Crawford (1928) in my inspection of the Yegua Knobs area. Yet I did observe seams of lignite nearby, and lignite crops out at least locally in the upper Calvert Bluff Formation of much of this part of East-Central Texas (Kaiser, 1978, p. 41 and fig. 5). The igneous rocks reported from Yegua Knobs may have been pyrogenic material resulting from underground combustion of coal. If this hypothesis is true, Hill's (1889) account preceded that of Lonsdale and Crawford (1928) as the first record of this process in Texas even though Hill had not correctly identified the material. Similar rocks have been reported from Williamson County, Texas; these apparently formed during extensive brush fires and did not involve combustion of coal (Keith Young, personal communication, 1983).

Despite their limited treatment in literature, sites of ancient burns probably are common in Texas just as in other areas. Theophrastus (translators' footnote 15, Agricola, 1950, p. 34, 35, see also p. 607), writing 2,300 years ago, gave a brief but accurate description of clinkers formed by natural burns in the Mediterranean regions. Cancrinus (1980, p. 51, 52; paragraphs 101, 102), in the late 1700's, also mentioned clinkers and distinguished the earthy and glassy phases of vitrification. Bentor and Kastner (1976) reported that evidence of natural burns has been recognized in Australia, India, Iran, and Israel, and in California in this country. Church and others (1979) identified such a site in British Columbia. Rogers (1917) concluded that seams of coal in more than one-half million square kilometers (200,000 mi^2) of Montana and adjoining states had been burned. So extensive were these underground fires that the resulting, porous clinker and slumped beds constitute important shallow aquifers in Montana and Wyoming (Hardaway, 1976, p. 8).

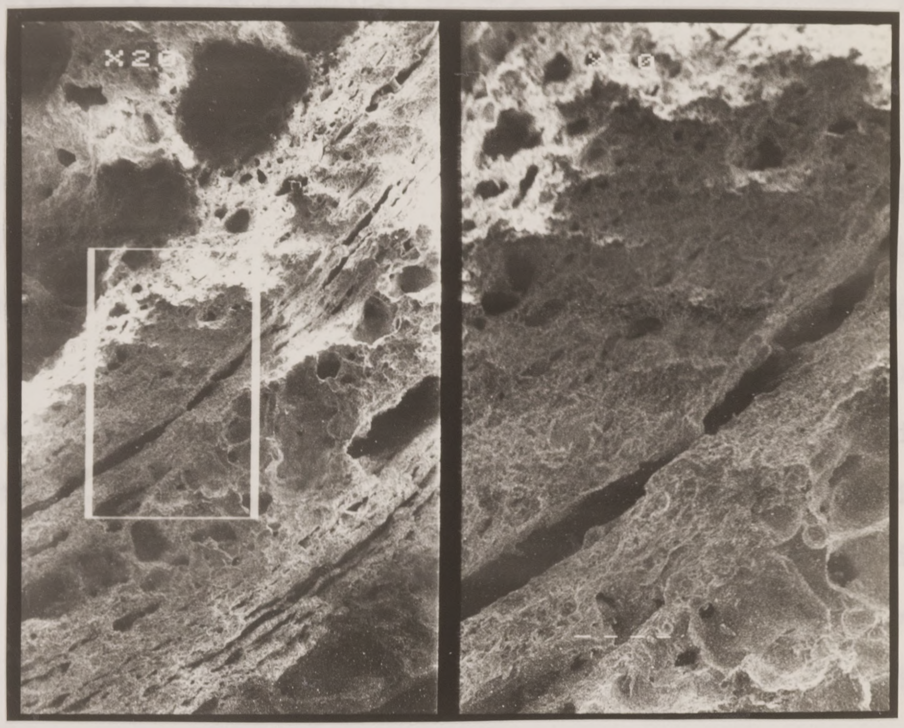
Where the fused strata crop out they facilitate exploratory mapping in areas of otherwise limited exposure. Slumping and subsidence above the burned and heavily oxidized coal generally cover the seams themselves. Many investigators (for example, Crow, 1938, p. 235, 236) have noted anomalous discontinuities in the outcrops of Texas coals. Some of these breaks may be related to surficial slumping. Oxidation of the coal at these sites could have initiated these mass movements even if the temperature of ignition never was reached. Oxidation causes slacking or disaggregation of coal at its outcrop, which tends to produce a recessive weathering profile. Continued slumping may seal the seam from further deterioration but also would effectively obscure the former outcrop. Subsidence induced by oxidation is a common occurrence in areas where bodies of ore rich in sulfides crop out, as in Arizona (Wisser, 1927). In fact, Wisser (1927, p. 761) has suggested that subsidence features of this type may affect overlying, unmineralized rock as much as 300 m (1,000 ft) above a buried mass of ore, and therefore are useful guides in exploration.

Indirect Assessment of Temperature

As noted previously, little reliable data exists regarding temperatures of underground fires in coal. There have been few attempts to measure the sensible heat produced within a burning seam or spoil mound. Yet adequate characterization of these thermal conditions is needed both for assessment of impact and mitigation planning. Temperature is an important factor governing environmental effects of fires in bedded coal and lithic wastes, because it may influence or control: the chemistry of leachates and vagrant fumes; the risk of continued or expanded burns; and the suitability of spoil that might be used in reclaiming a site. A reconstruction of the thermal history of a burn would address these topics. In addition, such information could be used to ascertain the horizontal and vertical extent of an underground fire, as indicated by the degree of heating to which samples from different parts of a site had been subjected. Clearly, a simple technique for estimating the temperatures attained during combustion would have many applications.

During this study I developed an indirect method by which to infer the temperature of a burn. I learned that shale from many of the state's coal mines had been used in industrial ceramics. More than sixty years ago, while many of the mines still were in operation, the shale was tested for possible use in manufacturing bricks and other products. Empirical data from these tests provide an indication of the thermal conditions under which clinker or "slagite" forms. Clays in the shale are complex mixtures of minerals. Unlike simple compounds, these mixtures pass from the solid to the liquid phase in several stages. Each stage reflects the relative extent to which that material melted and subsequently fused or vitrified. Thus a sample of clinker bears evidence of the intensity of the burn in which it formed.

Appendix A is a summary of field descriptions of clinker (eight samples) from nine sites in the Texas counties of Bastrop, Eastland, Palo Pinto, and Young. Three distinct stages of fusion are evident in these samples, corresponding to different temperatures of formation. The first stage is indicative of the lowest temperature at which effects of heat are discernible. This threshold is incipient fusion which occurs at and somewhat above the "eutectic" or initial-melting temperature of an argillic material. At this stage (fig. 16) most of the material is solid, but some of the finer grains and the more unstable constituents of the shale begin to liquify, filling a small percentage of the interstices between and within individual particles of shale. Laminae within the shale begin to fuse, reducing intraparticular porosity. Conversely, some laminae may separate if the interlaminar material melts. Minute bubbles form in the resulting liquid and seem to aid in separating the remaining laminae. The gas within these bubbles may include water vapor although data from Potter and McKnight (1931, p. 65-67, 102-108) indicate that most of the water probably was driven out of the shale at lower temperatures during the prolonged period of gradual heating.



(a) (b)

Figure 16. Scanning-electron micrograph of partly fused shale from the spoil mound at mine-site number Ea/BL-1-1, Eastland County, Texas. Although the original lamination of this particle of shale remains evident, some laminae had begun to fuse (see enlargement on right), indicating that the clast attained incipient fusion before chilling. The clast was deformed slightly, due to the weight of overlying debris composing the mound. (a) Magnification is x 20. (b) Inset area in (a) magnified x 60; each of the four increments in the bar-scale is 100 microns in length.

A more likely explanation for the appearance of bubbles is thermal generation of gaseous carbon dioxide or carbon monoxide. Both oxides are products of the combustion or distillation of bituminous matter of which a small amount generally is disseminated through the shale (Potter and McKnight, 1931, p. 59-61). These gases also are produced by combustion of particulate coal mixed with the shale. Evolved gas may diffuse into the shale along shrinkage fractures or porous laminae, but this hypothesis is untested. An additional, minor source of carbon dioxide is calcium carbonate and perhaps traces of other carbonates. Any calcium carbonate that was not leached by sulfuric acid (a product of the oxidation of pyrite) would be calcined by the extreme heat, forming calcium oxide and carbon dioxide gas (Potter and McKnight, 1931, p. 66). This gas may emanate through or between the clasts of shale. Interstices within the margins of the clasts subsequently may become filled with liquid (rock-melt). If this happens the bubbles, regardless of their origin, would be entrapped. With continued heating these bubbles would expand, distorting the laminae. The additional heat also would soften the clast causing further distortion. Compression of the softened clast reorients the bubbles along preferred planes reflecting the local state of stress rather than the original sedimentary lamination. Chilling the clast at this stage would preserve the pattern of bubbles as vesicles in interlaminar glass.

When the temperature of the clast has advanced still further, all or nearly all (more than 99 percent) of the interstices fuse or become filled with melt (fig. 17). At this stage the clast is vitrified, the second stage of pyrogenesis. A clast may deform to a limited extent at temperatures between those of incipient fusion and vitrification. Migration or local generation may concentrate bubbles of gas which would tend to enhance deformation. But the clast as a whole supports its own mass and generally retains its shape, although some additional compaction and folding may occur because of the load of the overlying material. The volume of the clast is reduced to a minimum by fusion. Oxidation of bituminous matter, calcination of calcite, and dewatering certainly are complete by this stage. Gas no longer may diffuse into a clast but may pass through the melt (the "proto-hyalic" material) along interconnecting pores between clasts. The sedimentary lamination of the shale generally is obscured or represented only faintly. Lines of bubbles may correspond to the original lamination in some samples. Chilling would cause the interior of the clast to become entirely glassy and dense to

Figure 17. Scanning-electron micrograph of partly and completely fused shale from spoil mound at mine-site number PP/G-2-9, Palo Pinto County, Texas. Vitrified shale (areas left of center and in lower right), magnified x 18. Each of the four increments in the bar scale (center-right, bottom) is 100 microns in length.

moderately porous. All remaining clasts would be held in a matrix of glass, yet there may be glass-free openings through the mass. The vesicularity of the glass may range from slight to extreme.

At even higher temperatures the clasts liquify completely, at the third and final stage, viscous fusion (fig. 18). No longer able to support their own mass, the clasts flow into one another, closing all intergranular pores. The ratio of amorphous liquid to definable clasts increases. Eventually, there may be no suggestion of the outlines of individual clasts. The viscosity of the liquid decreases; flowage is spontaneous and does not require compaction of the clasts.

Several factors probably affect the viscosity of the liquid: (1) temperature; (2) chemical composition of the melt, reflecting that of the parent rock; (3) type and amount of gas in solution; and (4) size and concentration of bubbles entrained in the liquid. The most obvious indication of differences in the viscosities of melts after they have chilled and solidified is the vesicularity of the glass. Vesicles are distributed throughout the glass, and over those surfaces that represent the "free" or unconfined boundaries of melt-filled vugular spaces within the matrix. Vesicles on the surface of the glass usually form open

Figure 18. Scanning-electron micrograph of completely fused shale from spoil mound at mine-site number PP/G-2-9, Palo Pinto County, Texas. Viscously fused shale. Central part of fig. 17, magnified to x 75. Leftmost increment in the bar scale is one micron in length. Fractures formed when melt-liquid chilled and solidified as bubbles of gas were contracting owing to the reduction in temperature. Surfaces on opposite sides of fractures are in different planes.

chambers or closed, well-defined prominences such as spherical domes. One extremely porous sample, number B1H from Bastrop County (mine site Ba/Ba-4-1), consists of 80 percent glass and only 20 percent clasts. The glass is highly vesicular yet virtually no vesicles break its surface as chambers or prominences. This near absence of vesicles marking the surface of the glass indicates that the viscosity of the melt was especially great. The cause of this anomalous viscosity was not immediately apparent. In particular, the concentration of bubbles in the liquid was very high which should have reduced the viscosity. Too, the temperature was high, as implied by the large percentage of glass in this sample. Some other property of the liquid appears to have increased its viscosity. Its chemical composition, including that of the dissolved gases, is the probable cause of this effect. The existence of intrinsic differences of this kind in the clinkers from different localities is not unexpected, yet it does imply a need for careful examination and comparison of samples when interpreting the maximum temperatures of melts.

Empirical data are needed to relate petrographic textures in clinker to specific temperatures of pyrogenesis. Ceramic testing provides this data. Ceramicists employ a descriptive nomenclature, supported by physical testing, to characterize the thermally-induced behavior of clays which affects their suitability for various uses. These clays, when heated, pass through stages of vitrification that are conceptually identical to the stages of fusion seen in samples of clinker. So conspicuous is this similarity that in my field descriptions of clinker (appendix A), I have chosen to incorporate the ceramicists' terms for these stages: incipient fusion; vitrification; and viscous fusion. Thus, by referring to data from tests of fusibility, one may estimate the temperature at which the clinker formed. This temperature presumably was the maximum local temperature of the fire. The comparison is valid only if the material tested was at least representative of the lithic wastes placed in the spoil mounds and which later formed clinker. Ideally, tests would have been performed on clays from the same mines at which the clinker was collected, or from mines nearby or within the same stratigraphic horizon.

A reliable analogy can be made at such sites because the material within the spoil mounds where the clinker formed is that which was in greatest supply and could be most easily exploited for making bricks or other fired products. Ries (1908) investigated the fusibility of clays from coal mines in Texas (table 3). The temperatures

Table 3. Fusibility of clays from coal mines in Texas[1]

Sample number (Ries, 1908)[2]	Sampling locality	Description of sample	Percentage of air shrinkage	Temperature (T: °C,°F), Shrinkage (S: %) absorption (A: %)[4]: Incipient fusion[5]	Vitrification[6]	Viscuous fusion[7]
943	Eastland Co. bituminous coal mine 8km (5 mi) northwest of Cisco	Blue shale collected from bed overlying coal seam, 12m (40 ft) below ground in mine. Fires to red-buff color. High organic content	8.6	T: 1150°C (2102°F) S: 6.7 A 5.9		T: 1310°C (2390°F)
944	(Same)	Blue shaley clay collected from bed underlying coal seam. Fires to buff color	6.6	T: 1050°C (1922°F) S: 2.0 A: 11.5	T: 1230°C (2246°F) S: 5.4 A: 4.2	
846	Erath Co., bituminous coal mine near Thurber	Clay fires to brown color. High organic content. Used in brick-making	6.4	T: 1050°C (1922°F) S: 2.3 A: 6.5	T 1150°C (2102°F) S: 4.0 A: 4.7	T: 1190°C (2174°F)
848	(Same)	Black clay. Fires to brown color. Used in brick-making	7.7	T: 1050°C (1922°F) S: 5.6 A: 3.6	T: 1190°C (2174°F) S: 6.3 A: 0.1	T: 1230°C (2246°F)
814	Milam Co., Olsen's lignite mine, Rockdale.	Gray, dense, shaley clay. Fires to buff, shading to gray at high temperatures. Used as fire clay.	6.7	T: 1050°C (1922°F) S: 1.0 A: 11.3	T: 1310°C (2390°F) S: 2.1 A: 4.2	T: 1670°C (3038°F)

827	Milam Co., shaft of lignite mine 5.6km (3.5mi) north of Rockdale	Dark gray clay collected from bed underlying coal seam, 18m (58ft) below ground in mine. Fires to buff color. High organic content.	11.6	T: 1050°C (1922°F) S: 2.7 A: 6.1	T: 1310°C (2390°F) S: 8.0 A: 2.5	T: 1410°C (2570°F)
829	Milam Co., Vogel's lignite mine, Rockdale	Dark clay collected from bed underlying coal seam. Fires to buff color. High organic content.	9.1	T: 1050°C (1922°F) S: 2.0 A: 10.3	T: 1410°C (2570°F) S: 6.0 A: 0.2	T: 1670°C (3038°F)
830	Milam Co., near Vogel's lignite mine, Rockdale	Sandy clay collected from ground surface. Fires to red color	9.3	T: 1050°C (1922°F) S: 1.0 A: 12.1	T: 1230°C (2246°F) S: 3.5 A: 3.1	T: 1350°C (2462°F)
802	Webb Co., cannel-coal mine near Minera	Shale collected from bed underlying lower coal seam. Fires to buff color.	10.1	T: 1050°C (1922°F) S: 3.0 A: 4.7		
803	(Same)	Shale collected from bed interfingering coal seam. Fires to buff color	9.6	T: 1050°C (1922°F) S: 5.0 A: 2.0	T: 1090°C (1994°F) S: 6.0 A: 0.0	
804	Webb Co., cannel coal mine near Cannel	Shale collected from bed underlying lower coal seam. Fires to buff color.	8.0	T: 1050°C (1922°F) S: 4.3 A: 8.2	T: 1310°C (2390°F) S: 6.0 A: 4.2	T: 1410°C (2570°F)

805	(Same)	Weathered shale. Fires to light color at low temperatures, and to brown color at temperatures greater than 1150°C (2102°F).	9.1	T: 1050°C (1922°F) S: 4.0 A: 8.8	T: 1230°C (2246°F) S: 6.2 A: 6.6
930	Wise Co., shaft of bituminous-coal mine near Bridgeport	Hard, dense, shaley clay. High organic content.	7.3	T: 1050°C (1922°F) S: 5.3 A: 7.3	T: 1090°C (1994°F) S: 8.0 A: 2.4

[1]Sample collected at coal mine in Texas and tested by Ries (1908). Many other tested samples were collected in counties and communities in which coal was mined but the locality listings for these samples did not state or clearly imply that they were from coal mines.

[2]Ries (1908) tested the ceramic qualities of clays from throughout the state. Chemical and physical analyses of all the clays discussed here are included in Ries' report. Ries' data (physical and chemical) were reiterated in condensed and tabulated form by Potter and McKnight (1931, p. 167-175 and tables 1 and 2).

[3]Percentage of volumetric shrinkage resulting from partial drying in air prior to firing.

[4]Temperature: temperature at which fired clay enters one of the three stages of fusion. The temperature was determined by the onset of melting of one of a standardized series of ceramic materials that were fired simultaneously. The melting point of this ceramic material ("cone") is calibrated to an accuracy of 10 to 15 degrees Celsius (18 to 27 degrees Fahrenheit). Fire shrinkage: percentage of volumetric shrinkage resulting from firing to one of the stages of fusion. Maximum shrinkage is attained at vitrification; continued heating does not affect the volume of the sample. Absorption: a measure of the relative porosity of the fired sample at one of the stages of fusion. Absorption is determined by weighing the sample before and after impregnation with a liquid; the increase in weight (that is, the weight of the liquid absorbed) after impregnation is expressed as a percentage of the original weight.

[5]Stage of relative fusion at which part of the fired sample first begins to melt, filling some of the interstices between remaining solid grains with liquid (which, upon chilling, becomes glass).

[6]Stage of relative fusion at which most of the fired sample fuses and all or nearly all of the interstices between solid grains are filled with liquid.

[7]Stage of relative fusion at which the fired sample is completely fused and can no longer support its own load, resulting in plastic deformation.

See also Potter and McKnight (1931, p. 42, 43, 61-73).

of fusion (incipient to viscous) given in table 3 are compatible with estimates of temperatures attained during (1) *in situ* gasification of coal, and (2) incomplete combustion of carbon as discussed previously. Therefore, ceramic tests appear to provide data suitable for estimating the temperatures of burns.

A second, potential source of indirect evidence concerning temperatures of combustion also was evaluated. Cooper and others (1948, p. 58-63) tested the fusibility of mineralic ash from Texas coal. Conceptually, these data did not appear to be as meaningful for the present purpose as those from the ceramic tests. But comparison of the temperatures of fusion of shale and ash demonstrates that these two kinds of data are reasonably consistent, as shown in table 4. Tests of fusibility were performed on 13 samples from 8 mine sites in 5 counties. Samples of Pennsylvanian (Strawn, Cisco, and Canyon Groups) and Eocene (Wilcox and Claiborne Groups) shale are represented. These shales were associated with bituminous, canneloid, and lignitic coals. The temperatures of incipient fusion of clay in the samples ranged from 1,050 to 1,150°C (1,922 to 2,102°F), but all but one of the clays had begun to fuse at 1,050°C (1,922°F). This is roughly comparable to the range in the temperatures of "initial deformation" of mineralic ash, 1,004 to 1,471°C

Table 4 . Summary of data on the fusibility of clays and mineralic ashes associated with coal in Texas.

CLAY (Ries, 1908)			COAL ASH (Cooper and others, 1948)	
Stage	Temperature	Agreement	Temperature	Stage
Incipient fusion	Range: 1,050 to 1,150°C 1,922 to 2,102°F Mean: 1,100°C 2,012°F Variation: 50°C 90°F (4.5% of mean)	78.2 to 95.6%	Range: 1,004 to 1,471°C 1,840 to 2,680°F Mean: 1,237.5°C 2,260°F Variation: 233.5°C 420°F (18.9% of mean)	Initial Deformation
Vitrification	Range: 1,090 to 1,410°C 1,994 to 2,570°F Mean: 1,250°C 2,282°F Variation: 160°C 288°F (12.8 % of mean)	92.0 to 97.2%	Range: 1,060 to 1,532°C 1,940 to 2,790°F Mean: 1,296°C 2,365°F Variation: 236°C 425°F (18.2% of mean)	Softening
Viscous fusion	Range: 1,190 to 1,670°C 2,174 to 3,038°F Mean: 1,430°C 2,606°F Variation: 240°C 432°F (16.8% of mean)	91.4 to 94.1%	Range: 1,088 to 1,571°C 1,990 to 2,860°F Mean: 1,329.5°C 2,425°F Variation: 241.5°C 435°F (18.2% of mean)	Fluid

(1,840 to 2,680°F), in coal from the same counties and some of the same mines (Cooper and others, 1948, p. 58-63). The mean of these temperatures was higher than that from the ceramic tests, possibly because the observed phenomena, incipient fusion and initial deformation, are slightly different. Visible deformation of a sample probably occurs at a temperature higher than that required for the onset of internal fusion. The discrepancy may be more apparent than real but it does make precise comparison of these data more difficult.

Better agreement is obtained when the temperature of argillic vitrification is compared to the "softening temperature" of ash. Vitrification of clay occurred between 1,090 and 1,410°C (1,994 and 2,570°C), with most readings between 1,150 and 1,310°C (2,102 and 2,390°F). Softening of ash occurred between 1,060 and 1,532°C (1,940 and 2,790°F) in samples from the same counties and statewide, with most values clustering between 1,060 and 1,349°C (1,940 and 2,460°F). Vitrification represents the threshold of significant deformation which is very similar to the physical manifestation of "softening." Therefore, these data are directly comparable.

Both the temperature of viscous fusion of clay and the "fluid temperature" of ash vary over a broad range of values, and yet these two sets of data are in relatively close agreement (within five percent). Viscous fusion was observed between 1,190 and 1,670°C (2,174 and 3,038°F) and the data are fairly equally distributed through this wide range. Ash from these same counties became fluid between 1,088 and 1,571°C (1,990 and 2,860°F), with some clustering toward the middle of this span. Considerable variation in the data is not surprising. The temperature of complete melting (viscous fusion or fluidization) is an intrinsic property and clay and ash are unique and complex mixtures of mineralic substances. Each mixture is likely to respond to extreme heat in a singular manner, dictated by its most heat-resistant component. This points to a need for conservative extrapolation of the data from one test to other materials in different locations and geologic settings. Overall, analyses of firing characteristics, such as those reported by Ries (1908), are the more appropriate indicators of temperatures at which clinker formed. The phenomena analyzed and the conditions that constitute thresholds are identical to easily recognized stages of fusion in clinker. But data concerning the fusion of ash from coal are widely available since this test is a routine step in the determination of rank, firing characteristics, and potential production of aerosol pollutants (vagrant particulate matter). Availability increases the value of these data for the present purpose.

Samples of clinker from spoil mounds in Young, Eastland, Coleman, and Bastrop Counties reveal no major dissimilarities, despite obvious differences in their parent materials including the age, composition, stratigraphic provenience, and rank of their associated coal (appendix A). The fabic of virtually all samples was vesicular to finely porous. These pores exhibited two discrete morphologies, coarse and irregular or smooth and rounded. Irregular pores (such as those in the upper left corner of fig. 17) appear to have been molded around angular fragments of shale or other materials that became brittle upon heating and brecciated after the melt solidified. Particles of coal that were not completely burned may have occupied some of these pores before slacking. Pores with rounded walls (such as those at the bottom of fig. 17) were produced when the heat was sufficient to evolve a vapor phase and the bubbles were suspended in a quick-cooling melt.

Figure 19 illustrates a large mass (measuring approximately 3 by 5 by 5 m, 10 by 16 by 16 ft) of vitreous clinker in the eroded spoil mound at an abandoned underground mine site (number Ea/BL-1-1)in Eastland County. The interior of the mound was fused by combustion that melted

Figure 19. Large mass of clinker in a spoil mound, mine-site number Ea-BL-1-1, Eastland County, Texas, 1979. Most of the material within the mound mass was at least partly fused.

the shale and other lithic debris as admixed particles of coal burned spontaneously. Thin sections were cut from a representative sample of this vesicular mass. Under crossed nicols the material is largely isotropic and therefore amorphous. Only the incorporated remnants of sedimentary rocks (shale and siltstone) are birefrigent. There are no crystalline materials in the glassy matrix, indicating that the burn remained hot long enough to completely melt the core of the mound, then chilled rapidly preventing crystallization. X-ray diffraction of cleaned specimens of the matrix reveal no cryptocrystalline patterns, confirming the vitreous character of this material.

Pyrogenic material from the spoil mound shown in figure 19 is distinctly different from the most coarsely crystalline specimens described by Lonsdale and Crawford (1928, p. 156-158). Where burning spreads deep into a seam or beneath a thick mantle of soil the melted rock may be sufficiently insulated to permit gradual cooling and consequent crystallization. In fact, a spectrum of pyrogenic textures should be expected in the vicinity of a burning seam or spoil mound, ranging from unaltered material to burned and oxidized rock, glass, and crypto-, micro-, and phenocrystalline clinker. Lonsdale and Crawford (1928, p. 154-158) observed a suite of low- to high-temperature low-pressure minerals and glass representing a nearly complete textural series. A complete series probably can be attained only within the thermal zone of an extensive, underground burn, or in a very large mound of spoil, for no comparable suite was found in those samples that were examined petrographically during the present study. However, the number of samples studied may not provide a sufficient basis for a generalization of this kind.

GEOCHEMICAL LEACHATES

Coal mines have long been recognized as major sources of pollutants. Acids were among the first naturally-occurring hazardous substances found to be part of the mine environment. In the late 1700's, Cancrinus (1980, p. 38: paragraph 23) reported that sulfuric acid evolved spontaneously from the oxidation of pyrite and other sulfides associated with coal. This process is now well known. Yet, despite this knowledge, control of acidic mine drainage remains difficult. Acidic pollution resulting from mining operations, principally coal mining, has degraded more than 19,3000 km (12,000 mi) of streams in the United States (Warner, 1970). This is a conservative estimate because it incorporates incomplete data from several states including Texas.

The major pollutants existing in coal mines, spoil mounds, and their liquid effluents are sulfuric acid, sediment, and concentrations of toxic or otherwise undesirable elements and radicals (U.S. Environmental Protection Agency, 1975, p. 5, 11). These substances may degrade soils, runoff, and ground water at mine sites. Streams and reservoirs nearby may be affected as well.

Suspended sediment reduces penetration of light and coats the feeding structures, gills, and eggs of many free-swimming aquatic organisms (McKee and Wolf, 1963, p. 280, 281). As the sediment drops out of suspension it covers benthic organisms in streams and impoundments. In upland areas redistributed sediment may bury plants and productive soils (fig. 20). Deposition and erosion are perhaps the most conspicuous adverse environmental effects at mine sites in Texas. These processes are discussed at length in a later section of this thesis.

Sulfuric acid is produced in coal mines and spoil mounds when sulfides oxidize in the presence of water; a more complete description of this complex process is given later in this section. Hydrogen ion concentrations in solutions of dissociated sulfuric acid may poison soils and reduce the pH of natural waters to between 4.5 and 0.0 or even less (Krauskopf, 1967, p. 35). Such conditions are lethal to virtually all organisms except some acidophilic and acid-tolerant microbes (Nordstrom, 1977, p. 57-61). Sulfate is the other dissociation product. Sulfate greatly increases the amount of dissolved solids in waters, which generally is expressed as salinity. This renders the water toxic or otherwise unsuitable for most uses at only moderate concentrations (Caran, 1978, p. 50, 51).

Figure 20. Oblique aerial photograph of devegetated area around a large spoil mound at mine-site number PP/G-2-54, Palo Pinto County, Texas, 1979. Sediment eroded from the mound buries vegetation nearby. Phytotoxic leachates (particularly sulfuric acid and toxic metals) kill and prevent reestablishment of plants on and around the mound. Photograph by William Hupp, Texas Department of Water Resources (used with permission).

Extreme acidity also increases the solubility and therefore the ionic concentration of many other pollutants produced in mining coal. At high concentrations the pollutants readily become biologically assimilable. Metals such as aluminum, arsenic, manganese, nickel, selenium, strontium, and zinc are phytotoxic or zootoxic at concentrations well below those commonly observed at mine sites (U.S. Environmental Protection Agency, 1975, p. 11-19; Gough and others, 1979). Molybdenum also can become toxic under certain circumstances (Dollahite, 1972).

The effects of various pollutants may be additive. For example, one of the major factors contributing to the redistribution of sediment at coal mines is the reduced vegetative cover typical of these sites. Acidity and toxic solutes can cause or contribute to devegetation, thereby promoting erosion. And because the biological activity of most of the phytotoxic metals is linked to pH, it is clear that acidity is one of the principal causes of the deterioration of mine sites. For this reason, the production of sulfuric acid must be the focus of any discussion of geochemical effects of coal mining.

Formation of Acids in Mine Spoil

Sulfuric acid (solution) is a product of the dissolution and oxidation of sulfide minerals in air and water. Nordstrom (1977, p. 54) reviewed the general sequence of reactions describing the decomposition of pyrite and similar sulfides in soils and fresh waters of initially normal chemistry. The primary reaction is oxidation of the sulfide minerals pyrite, the isometric ferrous sulfide, and marcasite, its orthorhombic dimorph, thereby forming ferrous iron and sulfur. The oxygen in this reaction is atmospheric. Where oxygen is the sole oxidant, oxidation of pyrite proceeds at a rate proportional to the partial pressure of oxygen such that diffusion of oxygen is rate limiting (Nordstrom, 1977, p. 52). This relation also is seen at coal mines, where the oxygen typically is dissolved in the intergranular water of a spoil mound, or in interstitial ground water in bedded coal. As represented here, the initiating reaction is a transition from mild acidity (probably related to the presence of organic acids) to neutrality:

$$FeS_2(s) + 1/2\ O_2(aq) + 2H^+(aq) = Fe^{2+}(aq) + S_2^{\circ}(aq) + H_2O.$$

Following this reaction the ferrous ions are rapidly oxidized and hydrolyzed at the then neutral pH, thereby precipitating ferric hydroxide:

$$Fe^{2+}(aq) + 1/4\ O_2(aq) + 5/2\ H_2O(aq) = Fe(OH)_3(s) + 2H^+(aq).$$

The above reaction restores a mildly to moderately acidic pH. Ferric hydroxide is an insoluble, amorphous substance called "yellow boy" which covers the bottoms of most streams and impoundments affected by acidic mine drainage (Down and Stocks, 1977, p. 110, 111). However, other precipitates of iron hydroxide may form as well, depending on the prevailing pH and concentration of iron. Brown (1971, p. 245-248) found that if sufficient iron is present in solutions that have a pH greater than 3, goethite (or possibly hematite) is the stable phase; whereas at a lower pH and in the presence of oxidants, jarosite is stable if sufficient sulfate and potassium also are available. Other minerals may form under special conditions (Nordstrom, 1977, p. 54).

Reactions continue as neutral sulfur compound, a product of the initial reaction, is oxidized to sulfate, thereby significantly lowering the ambient pH:

$$S_2^{o}(aq) + 2\ O_2(aq) + 2H_2O\ (aq) = 2S\ O_4^{2-} + 4H^+(aq).$$

As the pH falls hydrolysis of ferric iron slows. Simultaneously there is a significant increase in the activity of ferric iron such that it becomes the major oxidant at pH values below 3 and in the absence of oxygen (Nordstrom, 1977, p. 52). These conditions can exist only within the interior of coal mines and large spoil mounds. The acidic, sulfate-rich solution above promotes the following reaction which greatly increases the concentrations of hydrogen ions (further reducing the pH) and ferrous iron:

$$FeS_2(s) + 14\ Fe^{3+}(aq) + 8\ H_2O(aq) = 15\ Fe^{2+}(aq) + 2\ SO_4^{2-}(aq) + 16\ H^+(aq).$$

Pyrite is rapidly oxidized in the presence of ferric iron. However, the oxidation of ferrous iron to ferric is very slow at pH values below 4 so that the formation of ferric iron becomes rate limiting (Singer and Stumm, 1970, p. 1121). The above reaction thus would be impeded were it not for acidophilic, aerobic, aphotic, ferrous-oxidizing bacteria, especially the Thiobacillus-Ferrobacillus group (Kuznetsov and others, 1963). These bacteria produce ferric iron metabolically at rates several orders of magnitude higher than the abiotic rates at low pH (Nordstrom, 1977, p. 55). By this series of reactions microbial catalysis and atmospheric oxidation produce a self-perpetuating system which generates large quantities of sulfuric acid solution from pyrite and water.

The rate of decomposition of sulfide minerals is directly related to the size of the particles (Caruccio, 1973, p. 217) and their distribution relative to the permeability of their matrix. Oxidation is most rapid if the particles are fine and evenly distributed through a porous medium. Formation of sulfuric acid is greatest when, in addition, sulfide minerals constitute a significant percentage of the coal or rock. Spoil mounds at many coal mines in Texas provide these "ideal" conditions.

Sulfide Minerals in Coal and Spoil

The mineralogy of sulfides within the spoil mounds is a key factor in the formation of sulfuric acid, in part because it affects the size of crystals of ferrous disulfide that enter reactions. Arora and others (1978, p. 151), citing several previous studies as well as their own findings, stated that pyrite is less reactive (more resistant to weathering) than is marcasite, although pyrite is more abundant and thus the more important source of sulfide. However, the size and morphology of grains of pyrite greatly affect their rates of oxidation. Love (1967) and Caruccio (1973, p. 217) reported that pyrite crystallizes either as large, euhedral grains (discrete or clumped) or smaller, spheroidal aggregates of microcrystals known as framboids.

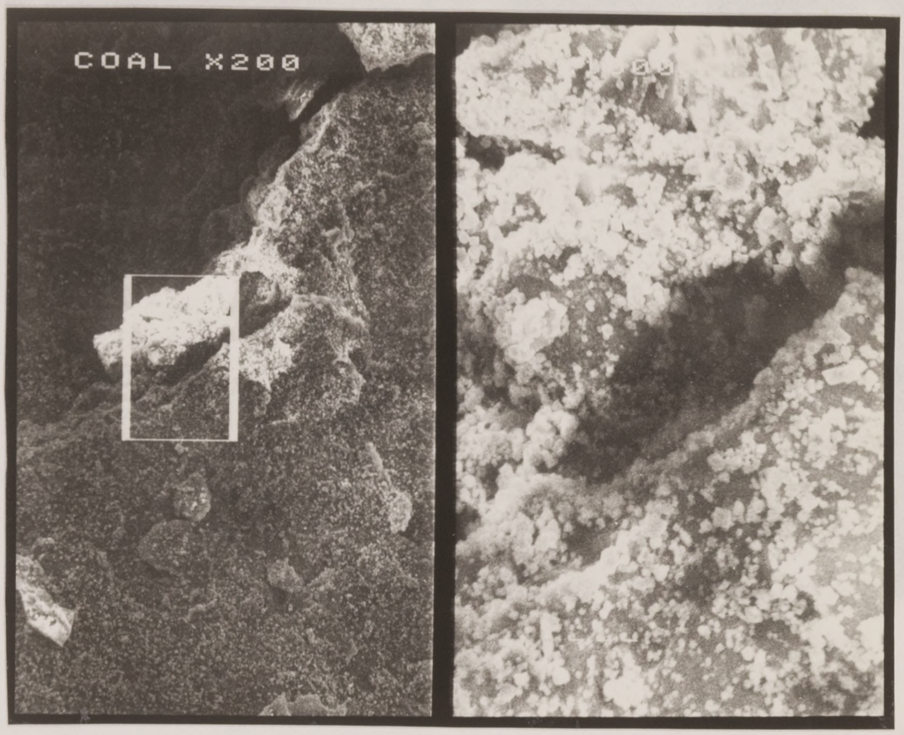
Horne and others (1978) concluded that framboids are the only form of pyrite that oxidize rapidly and are a significant contributor of sulfuric acid in the Appalachian region. This observation is consistent with that of Caruccio (1973, p. 206) who stated that:

> On the average, coals containing pyrite grains measuring less than 10 microns in diameter yielded 2-1/2 times more acid than coals continuing pyrite grains measuring greater than 150 microns.

In Texas few detailed descriptions of the sulfide minerals in coal have been published. Arora and others (1978) investigated the morphology of pyrite in lignitic coal and associated strata from the Wilcox Group of East-Central and northeastern Texas. These investigators (p. 154) reviewed much of the literature pertaining to the morphology of pyrite worldwide, particularly in coal, and found the most common forms to be euhedral crystals, framboids, and polyframboids or irregular aggregates of framboids. Each of these forms was observed in samples from Texas but the predominant morphologies were framboids and irregular, porous masses 20 to 50 microns in diameter, consisting of microcrystals 0.25 to 1.5 microns in diameter. The small size of each grain provides a large surface relative to its mass. From these observations Arora and his coworkers (p. 151) concluded that the oxidation of microcrystalline pyrite, and consequent formation of acid, could proceed quickly under appropriate conditions such as those existing within many spoil mounds.

The morphology, abundance, and distribution of sulfides in Pennsyvlanian bituminous coal from North-Central Texas was assessed qualitatively during the current study. Figures 21 and 22 are a progressive-magnification series of scanning-electron micrographs showing a single sample of weathered coal. This sample was collected from the eroded exterior of a spoil mound at mine site Er/G-2-63 near Thurber, Erath County. The surface shown in the figures was freshly exposed by splitting the moderately fissile sample along a bedding plane. This sample of ashy coal appeared to be covered with yellow dust. The micrographic series shows that the dust consists of discrete, euhedral, cubic microcrystals of pyrite that do not form framboids. Yet the size of the smallest of these crystals, 0.4 to 1.2 microns, is comparable to that reported by Arora and others (1978, p. 153) for crystals within framboids. Several samples of weathered shale and coal were examined with the scanning-electron microscope and light microscopes, but the only form of pyrite seen was the fine, euhedral crystal.

Some samples contained marcasite, generally in small, lenticular masses or thin sheets along laminae, in addition to disseminated, microcrystalline pyrite. Fresh

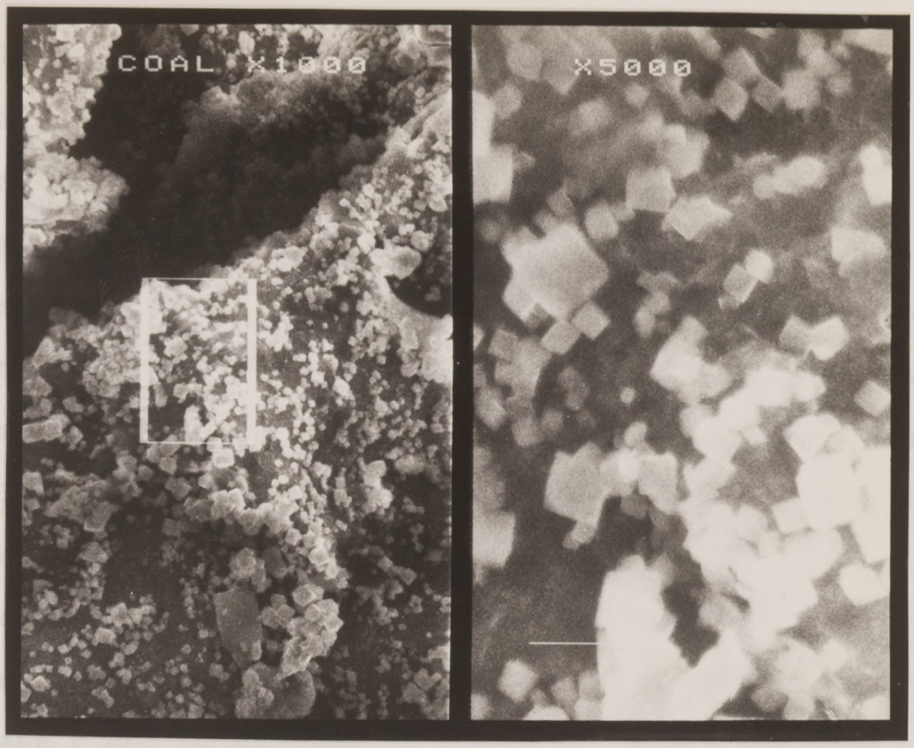


(a) (b)

Figure 21. Scanning-electron micrographs of microcrystalline pyrite on weathered coal from a spoil mound at minesite number Er/G-2-63, Erath County, Texas.

(a) Magnification is x 200.

(b) Inset area in (a) magnified to x 1000; each increment in bar scale is 10 microns in length.



(a) (b)

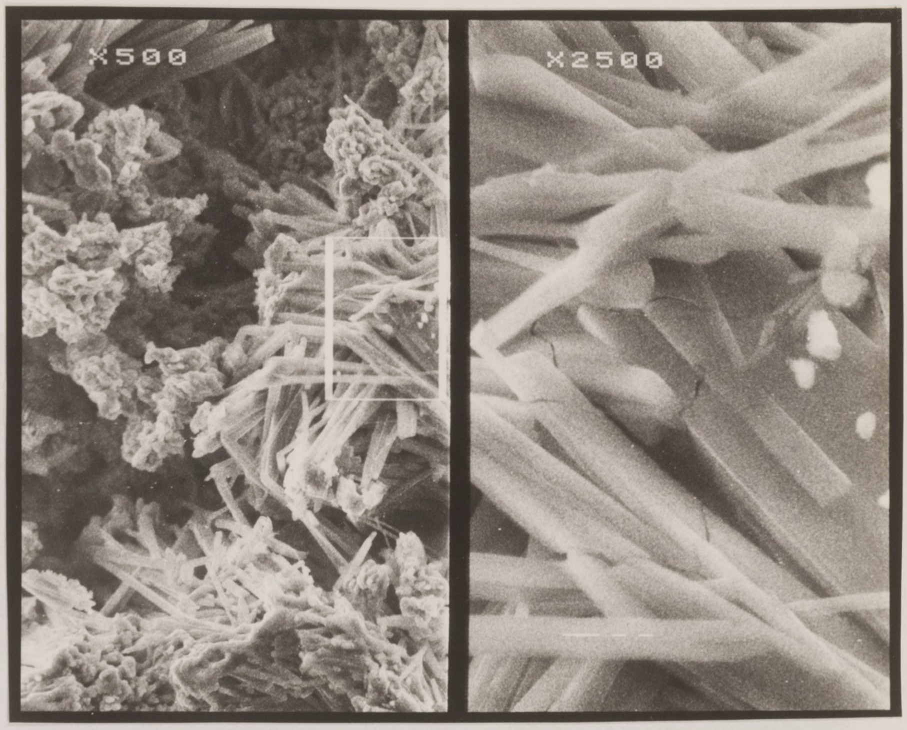
Figure 22. Scanning-electron micrographs of microcrystalline pyrite on weathered coal from a spoil mound at minesite number Er/G-2-63, Erath County, Texas.

(a) Magnification is x 1000 (area to the immediate upper right of that shown in fig. 17b).

(b) Inset area in (a) magnified to x 5000; leftmost increment in bar scale is 10 microns in length. Euhedral crystals of pyrite, the smallest of which are 0.4 to 1.2 microns in diameter.

samples of coal from the active mine at site Er/RM-4-20, Erath County, also contained small amounts of marcasite. Figure 23 is a coordinate pair of scanning-electron micrographs showing the freshly exposed surface of a sample recently mined at this site. This sample appears to have fractured across bedding, and some of the laminae separated around a small mass of marcasite. Despite these breaks the sample was hard and cohesive, indicating that fracturing and laminar separation probably occurred prior to mining. The micrographs reveal a dense, vermicular network of prisms of marcasite among aggregations of clay. These prisms are between 2 and 50 microns in diameter, about the same diameter as the framboids described by Arora and others (1978, p. 153). Some of the marcasite already had begun to decompose. Figure 24 shows a rosette of acicular prisms of melanterite, an alteration product resulting from oxidation and hydration of marcasite.

Marcasite and discrete microcrystals of pyrite probably oxidize very rapidly following exposure. Yet barren slopes at mine sites abandoned between 40 and 100 years ago in the Thurber mining district (fig. 20) attest to the persistence of conditions favorable for the formation of sulfuric acid. The large size of some spoil mounds permits gradual oxidation and release of acids. Perched ground



(a) (b)

Figure 23. Scanning-electron micrographs of marcasite in fresh coal from the active surficial mine at mine-site number Er/RM-4-20, Erath County, Texas.

(a) Magnification is x 500. Long thin crystals of marcasite with adhering plates of clay.

(b) Inset area in (a) magnified to x 2500; leftmost increment in bar scale is 10 microns in length. Fresh crystals of marcasite. Small white masses to right may be alteration minerals.

Figure 24. Scanning-electron micrograph of melanterite (?), $FeSO_4 \cdot 7H_2O$, monoclinic, a product of the oxidation and hydration of marcasite under atmospheric conditions. Magnification is x 5000, not x 500 as shown. Leftmost increment in bar scale is 1 micron in length. Melanterite tentatively identified by D. S. Barker, Department of Geological Sciences, The University of Texas at Austin.

water within the inhomogeneous mounds probably prevents or reduces the diffusion of oxygen to the interior. During periods of drought, in which the head of perched ground water decreases steadily, acid forms deep within the mounds. There, acidic solutions may become highly concentrated. Heavy metals that are more soluble at very low pH may concentrate as well. When this highly toxic solution or leachate is flushed out of the spoil by heavy rains the result is instantaneous destruction of plants growing on or around the mounds. This type of flushing action has been noted elsewhere (Agnew and Corbett, 1973), and is a major cause of toxic devegetation. A similar process of concentration likely occurs in small ponds on the surfaces of mounds (fig. 25). If erosion along the flanks breaches a pond concentrated leachate will wash down the slope.

There is little data concerning the geochemistry of leachate and perched water in spoil mounds at abandoned-mine sites in Texas. Finley and others (1979, p. 28) noted that standing water near some spoil mounds in North-Central Texas was oddly discolored or had an iridescent sheen unlike that produced by light-petroleum products. I also noted this phenomenon at other mine sites throughout the state. Geochemical conditions within these ponds may have been highly unusual. However, no analyses of these waters were

Figure 25. Oblique aerial photograph of small ponds on the surface of a spoil mound at mine-site number PP/G-2-51, Palo Pinto County, Texas, 1979. Mound is unstable and ponds may drain suddenly if retaining slopes fail. Photograph by William Hupp, Texas Department of Water Resources (used with permission).

performed. More convincing evidence of pollution is seen at sites at which "yellow boy," ferric hydroxide has precipitated within the impoundments. At site number Ea/CN-2-3, Eastland County, leachate emerging as base flow from a large spoil mound flows directly into a pond. At the point of entry a small delta of ferric hydroxide has precipitated within the impoundment. The beds of gullies and small streams that flow through mine sites generally are coated with this diagnostic material, indicating persistent, mildly to moderately acidic conditions.

Geochemical Analyses at Mine Sites in Texas

Table 5 summarizes results of several published analyses of coal, overburden, and spoil at active mine sites in the state. Toxic elements that may be expected to occur in significant concentrations at these mines and nearby abandoned sites are aluminum, arsenic, manganese, molybdenum, nickel, selenium, strontium, and zinc. These elements may remain concentrated at a site long after abandonment of the mine. Concentrations may in fact increase. However, the relation between whole-rock geochemistry and the composition of effluents and soils at mine sites is complicated by many factors. Among these are: (1) effects of flushouts; (2) the shifting boundary between

Table 5. Selected Geochemical Analyses of Samples from Coal Mines in Texas.

(Note: A variety of empirical techniques were employed by investigators in obtaining these analyses; see the references noted for descriptions of these procedures. Observations denoted by an asterisk (*) may be imprecise or otherwise unreliable.)

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	Geometric Mean	Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	River Water	TOXIC THRESHOLD: Plant	Animal
Acidity	Spoil, lignite mine; Freestone Co. (Hons and others, 1978, p. 212)		pH 3.8-7.6	Highly variable, generally pH 5-8.5 in agricultural soils (Coleman and Mehlich, 1957, p. 72.	Highly variable, generally pH 6.5-7.5 (Hem, 1970, table 3)	4.5>pH>9 (U.S.EPA, 1976, p. 181)	6.5>pH>9 (U.S.EPA, 1976, p. 178)
	Spoil at bituminous-coal mine; Palo Pinto Co. (Railroad Commission of Texas, unpublished records, 1980)		pH 3.86-5.24				
	Seepage and pore water in spoil at lignite mine; Freestone Co. (French, 1979, p. 62)		pH 5.1-7.3				
	Seepage water in two surficial lignite mines; Hopkins Co. (Railroad Commission of Texas, unpublished records, 1980)		pH 4.86-7.22				

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	Geometric Mean	Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	River Water	TOXIC THRESHOLD: Plant	Animal
Aluminum (Al)	Lignite ash; 39 samples; Central, eastern Texas	10,000 ppm	2,500-44,000 ppm	32,100-80,100 ppm (Hem, 1970, table 1)	0.07 ppm (Hem, 1970, table 1)	2-7 ppm in solution, sensitive species depressed; 14 ppm in solution, most species depressed (Gough and others, 1979, p. 5.	No reports of toxicity under natural conditions (Gough and others, 1979, p. 5)
	(Hildebrand and others, 1979, p. 36)						
	Coal ash; 12 samples; statewide		Approx. 50,000->100,000 ppm*		Al solubility increases at pH<6 and is very high at pH<4 (Hem, 1979, p. 111)		
	(Kohls, 1962, table 4)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES			BACKGROUND CONCENTRATION		TOXIC THRESHOLD	
	Description of Samples	Geometric Mean	Range of Observations	Clastic Sedimentary Rocks	River Water	Plant	Animal
Aresnic (As)	Lignite ash; 39 samples; Central, eastern Tx.	2.9 ppm	1-18 ppm	1-9 ppm (Hem, 1979, table 1)	0.005-0.336 ppm in U.S. domestic water supplies (U.S. EPA, 1976, p. 14)	0.5-100 ppm soluble As; some compounds more toxic (U.S. EPA, 1976, p. 16; Gough and others, 1979, p. 8, 9)	1.3-7 ppm in solution or forage; long-term exposure to lower concentrations may produce toxic symptoms. (U.S.EPA 1976, p. 16; Gough and others, 1979, p. 9, 10)
	(Hildebrand and others, 1979, p. 36)						
	Lignite and cannel-coal ash; 3 samples; McMullen, Webb, Zavala Cos.		Approx. 10-100 ppm*				
	(Kohls, 1962, table 4)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES			BACKGROUND CONCENTRATION		TOXIC THRESHOLD	
	Description of Samples	Geometric Mean	Range of Observations	Clastic Sedimentary Rocks	River Water	Plant	Animal
Cadmium (Cd)	Lignite ash; 45 samples; Central, eastern Tx.		<1-3 ppm	0.02-0.18 ppm (Hem,1979,table 1)	<0.001-0.01 ppm (U.S. EPA, 1976, p. 27, 28)	0.1-9 ppm in solution (U.S. EPA, 1976, p. 30); Gough and others, 1979, p. 16)	0.0004-4 ppm in solution (U.S.EPA 1976, p. 30; Gough and others, 1979, p. 17)
	(Hildebrand and others, 1979, table 3)						
	Lignite and cannel-coal ash; 2 samples; Fayette, Webb Cos.		Approx. 1-10 ppm*				
	(Kohls, 1962, table 4)						
	Water in small lake between spoil mounds at lignite mine; 4 samples; Milam Co.	0.00425 ppm (arithmetic mean)	0.002-0.006 ppm				
	(James and others, 1976, p. 160)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES			BACKGROUND CONCENTRATION		TOXIC THRESHOLD	
	Description of Samples	Geometric Mean	Range of Observations	Clastic Sedimentary Rocks	River Water	Plant	Animal
Chloride (Cl^-)	Pore water in spoil at lignite mine; Freestone Co. (French, 1979, p. 69)		400-1,690 ppm	15-170 ppm total Cl (Hem,1970,table 1)	1.9-30 ppm (Hem,1970, table 3)	1,300 ppm of NaCl in solution (Gough and others, 1979, p. 18). Few data available.	Range of lethal concentrations in water is narrow: 0.006-0.19 pm, most aquatic organisms killed (U.S. EPA, 1976, p.34). Soil-dwelling organisms may be affected similarly. No reports of toxicity through ingestion by terrestrial vertebrates (Gough and others, 1979, p. 17).

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	Geometric Mean	Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	River Water	TOXIC THRESHOLD: Plant	Animal
Manganese (Mn)	Lignite ash; 39 samples; Central, eastern Tx.	120 ppm	18-340 ppm	392-575 ppm (Hem,1970,table 1)	Relations complex and poorly understood but concentrations generally <<1ppm (Hem,1970, p. 126-131; U.S.EPA,1976, p. 96).	Highly variable: <1-150 ppm in solution in soils with pH<5 (U.S. EPA, 1976, p. 96; Gough and others, 1979, p. 33, 34). High sublethal concentrations of Mn cause many plants to accumulate excessive Mo (Purvis, 1955).	Highly variable: 1.5-50 ppm ingested, some invertebrates and cattle affected; 500-5,000 ppm ingested, some freshwater fish and most livestock affected (U.S.EPA, 1976, p.96; Gough and others, 1979, p. 34).
	(Hildebrand and others, 1979, p. 36)						
	Lignite ash; 48 samples; Milam Co.		Approx. 1,000-10,000 ppm*				
	(Duel and Annell, 1956, table 5)						
	Coah ash; 12 samples; Statewide		Approx. 30-10,000 ppm*	Excess Mn indicates geochemical mobilization under moderately to highly acidic conditions.			
	(Kohls, 1962, table 5)						
	Pore water in spoil at lignite mine; Freestone Co.		3-15 ppm				
	(French, 1979, p. 68)						
	Small lake between spoil mounds at lignite mine; 4 samples; Milam Co.	5.05 ppm (arithmetic mean)	3.9-5.6 ppm				
	(James and other, 1976, p. 170)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	GEOCHEMICAL ANALYSES: Geometric Mean	GEOCHEMICAL ANALYSES: Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	BACKGROUND CONCENTRATION: River Water	TOXIC THRESHOLD: Plant	TOXIC THRESHOLD: Animal
Molybdenum (Mo)	Lignite ash; 30 samples; Central, eastern Tx.	2 ppm	<1.5-7 ppm	0.5-4.2 ppm (Hem,1970,table 1)	0.00035 ppm (Hem, 1970, p. 200)	No reports of toxicity under natural conditions; many plants may accumulate high concentrations of Mo when the soil pH>5 (Dollahite and others, 1972, p. 49; Gough and others,1979, p. 36, 37).	Complex relations but inversely related to ingestion of copper; 5-10 ppm in forage causes toxicity in ruminants when concentration of Cu≤11 ppm (Gough and others, 1979, p. 37).
	(Hildebrand and others, 1979, p. 36)						
	Lignite ash; 48 samples; Milam Co.		Approx. 10-100 ppm*				
	(Duel and Annell, 1956, table 5)						
	Coal ash; 12 samples; Statewide		Approx. 3-300 ppm*				
	(Kohls, 1962, table 4)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	Geometric Mean	Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	River Water	TOXIC THRESHOLD: Plant	Animal
Nickle (Ni)	Lignite ash; 39 samples; Central, eastern Tx.	5 ppm	1.5-20 ppm	2.6-29 ppm (Hem,1970,table 1)	0.01 ppm (Hem, 1970, p. 201)	0.5-10 ppm (U.S. EPA,1976, p. 106; Gough and others, 1979, p. 39).	0.095-0.8 ppm in solution, many aquatic organisms affected; 700-1,600 ppm ingested, small vertebrates depressed (U.S. EPA, 1976, p. 105,106; Gough and others, 1976, p. 40).
	(Hildebrand and others, 1979, p. 36)						
	Lignite ash; 48 samples; Milam Co.		Approx. 1,000-10,000 ppm*				
	(Duel and Annell, 1956, table 5)						
	Coal ash; 12 samples; Statewide		Approx. 3-3,000 ppm*				
	(Kohls, 1962, table 4)						
	Small lake between spoil mounds at lignite mine; 3 samples; Milam Co.	0.0913 ppm (arithmetic mean)	0.083-0.1 ppm				
	(James and others, 1976, p. 172)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES			BACKGROUND CONCENTRATION		TOXIC THRESHOLD	
	Description of Samples	Geometric Mean	Range of Observations	Clastic Sedimentary Rocks	River Water	Plant	Animal
Selenium (Se)	Lignite ash; 39 samples; Central, eastern Tx.	6.8 ppm	2.7-16 ppm	0.52-0.6 ppm (Hem,1976,table 1)	0.001-0.05 ppm (U.S. EPA, 1976, p. 200)	No reports of toxicity under natural conditions; many plants may accumulate high concentrations of Se; (Gough and others, 1979, p. 40 ,41).	2-2.5 ppm in solution, many aquatic organisms killed; 0.5-5 ppm ingested, livestock affected (U.S.EPA, 1976, p. 200, 201; Gough and others, 1979, p. 42).
	(Hildebrand and others, 1979, p. 36)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES			BACKGROUND CONCENTRATION		TOXIC THRESHOLD	
	Description of Samples	Geometric Mean	Range of Observations	Clastic Sedimentary Rocks	River Water	Plant	Animal
Strontium (Sr)	Lignite ash; 39 samples; Central, eastern Tx.	100 ppm	20-200 ppm	28-290 ppm (Hem,1970,table 1)	0.06-0.11 ppm (Hem, 1970, p. 196,197)	No reports of toxicity under natural conditions; Sr contributes to water hardness which is inversely related to the toxicity of bivalent metals (U.S. EPA, 1976, p. 76).	
	(Hildebrand and others, 1979, p. 36)						
	Lignite ash; 48 samples; Milam Co.		Approx. 1,000-10,000 ppm*				
	(Duel and Annell, 1956, table 5)						
	Coal ash; 12 samples; Statewide		Approx. 10-3,000 ppm*	Excess Sr indicates geochemical mobilization under conditions of low pH.			
	(Kohls, 1962, table 4)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	Geometric Mean	Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	River Water	TOXIC THRESHOLD: Plant	Animal
Sulfur (S, total)	Lignite ash; 27 samples; Central, eastern Tx.	8,000 ppm	4,000-20,000 ppm	945-1,850 ppm (Hem, 1970, table 1)	3-56 ppm (Hem, 1970, table 3)	In high concentrations sulfate increases the dissolved solids of waters at mine sites and readily forms gypsum, $CaSO_4 \cdot 2H_2O$, in soils. Waters with dissolved solids in excess of 500-1,000 ppm generally are unsuitable for irrigation and can be highly injurious to native plants and wildlife. (U.S. EPA, 1976, p. 207-209). Ingestion of large amounts of $SO_4^{=}$ in forage also can enhance absorption and toxic effects of Mo when Cu concentrations are normal or low (Gough and others, 1979, p. 48).	
Organic S	(Same)	5,500 ppm	3,000-9,500 ppm				
Pyritic S	(Same)	1,200 ppm	100-15,000 ppm	Relative concentrations of the various forms of S at coal mines may indicate conditions favorable to formation of sulfuric acid, H_2SO_4, primarily through oxidation of mineralic sulfides ("pyritic S" in pyrite and marcasite).			
Sulfate ($SO_4^{=}$)	(Same)	200 ppm	100-1,200 ppm				
	(Hildebrand and others, 1979, p. 34)						
	Pore water in spoil at lignite mine; Freestone Co.		755-3,210 ppm				
	(French, 1979, p. 64)						
	Small lake between spoil mounds at lignite mine; 4 samples; Milam Co.	1,133 ppm (arithmetic mean)	890-1,433 ppm				
	(James and others, 1976, p. 155)						

CHEMICAL SPECIES OR PROPERTY	GEOCHEMICAL ANALYSES: Description of Samples	Geometric Mean	Range of Observations	BACKGROUND CONCENTRATION: Clastic Sedimentary Rocks	River Water	TOXIC THRESHOLD: Plant	Animal
Zinc (Zn)	Lignite ash; 39 samples; Central, eastern Tx.	7.7 ppm	1.9-46 ppm	16-130 ppm (Hem, 1970, table 1)	0.01 ppm (Hem, 1976, p. 204)	Complex relations, relative effects of companion metals poorly understood; possible toxic effects at 4-25 ppm Zn in solution (U.S. EPA, 1976, p. 247)but much higher concentrations generally are cited (Gough and others,1979, p. 56-58).	Highly variable: 0.01-0.87 ppm in solution, many aquatic organisms affected; >1,000 ppm ingested, most livestock affected (U.S. EPA, 1976, p. 246, 247; Gough and others, 1979, p. 58).
	(Hildebrand and others, 1979, p. 36)						
	Lignite ash; 48 samples; Milam Co.		Approx. 100-1,000 ppm*				
	(Duel and Annell, 1956, table 5)						
	Coal ash; 12 samples; Statewide		Approx. 10-3,000 ppm*				
	(Kohls, 1962, table 4)						
	Small lake between spoil mounds at lignite mine; 4 samples; Milam Co.	0.3392 ppm (arithmetic mean)	0.22-0.437 ppm				
	(James and others, 1976, p. 178)						

zones of oxidation and reduction within the mounds; (3) the variable solubility of minerals containing toxic metals; (4) the role of organic complexes and clays in releasing or binding metals; and (5) local neutralization of sulfuric acid by calcium carbonate in the spoil. Evidence of reactions with calcium carbonate (or other calcium compounds) is seen in the abundance of gypsum, the hydrous calcium sulfate, in the spoil at many mine sites.

Toxic Effects on Biota

Table 5 includes many analyses exceeding the given toxic thresholds of plants and animals. Toxic effects on vegetation are conspicuous at many abandoned mine sites in Texas. Devegetated areas on slopes and spoil mounds are common and appear to be expanding at some sites as spoil material is dispersed by erosion. Acidic soil and water may kill plants outright at pH values of less than 4.5-5.0 (U.S. EPA, 1976, p. 181). However, solubility of toxic metals increases greatly below this range and very likely would intensify the adverse effects on vegetation. Effects may be synergistic in complex ways. Increased concentrations of one element may increase or even decrease the overall susceptibility of a plant to the combined effects of several toxic metals, moderately to highly acidic conditions, and high concentrations of dissolved solids (salinity). For example, increased, near-lethal uptake of sulfate and manganese can be partly offset by fulfillment of a plant's corresponding requirement for additional molybdenum. However, nickle can be highly toxic to plants when the ambient pH is very low yet the increase in nickle concentration owing to greater solubility may be only small relative to background concentrations.

No instances of toxification of wildlife, livestock, or humans were found during this study. Most of the areas of mining are in sparsely populated regions, and severely affected sites generally have not been reoccupied for uses other than limited grazing. Yet there are potential effects on animals living near coal mines, including a disease of ruminants and other grazers that has been observed near abandoned uranium mines in South Texas (Atascosa, Ellis, and Karnes Counties) by Dollahite and others (1972). This disease, molybdenosis, is a serious, sometimes lethal ailment of cattle and sheep in particular that is brought on by a marked excess of molybdenum relative to copper in the diet (Dollahite, 1972, p. 47). Both at uranium and coal mines molybdenum commonly is concentrated in strata wherein the ambient pH normally remains low (table 5). Reducing conditions within uranium ore and overburden have produced high concentrations of molybdenum and some other heavy metals throughout large areas of South Texas (Henry and Kapadia, 1980, p. 4).

These mineralized strata enter the biosphere when they are excavated and mounded at the surface. Ranchers regrade the mounds and plant them with grasses after fertilizing and treating the spoil with lime to reduce acidity. At a pH near neutral, molybdenum is desorbed from iron and aluminum oxyhydroxides (Barrow, 1977). This mobile molybdenum then can be absorbed and concentrated by plants (Gough and others, 1979, p. 37). Many plants can assimilate molybdenum without toxic effects, and actually may require greater uptake of this element when concentrations of other heavy metals (particularly manganese, nickel, and zinc) also are high (Purvis, 1955). Grazing animals foraging these plants may ingest sufficient molybdenum to cause acute molybdenosis. The disease is particularly serious in ruminants, reducing vigor and possibly causing death in young animals. The ore at some uranium mines (particularly those in the Whitsett Formation of the Jackson Group) is associated with thin seams of lignite (Eargle and others, 1971). Therefore it is probable that molybdenum toxification could occur at coal mines in South Texas and other parts of the state. Programs to reclaim abandoned mines should take account of this hazard.

EROSION, SEDIMENTATION, AND HYDROLOGIC EFFECTS

The most common, adverse consequences of mining coal are: (1) redistribution and loss of sediment; and (2) the ensuing impact of sediment and runoff on terrestrial and hydrologic systems. Many of the activities inherent in the operation of a mine tend to increase local susceptibility to erosion and sedimentation, and alter the drainage, storage, and infiltration of water. Perhaps the best known examples of this relation were the effects of hydraulic gold mining in the Sierra Nevada (Gilbert, 1917). The mining of coal, both underground and surficially, also is widely known to have had a severe impact on water and land resources in many areas (Down and Stocks, 1977). Ninety-seven percent of the erosion in a small watershed in southeastern Kentucky was attributed to strip mining even though the mined area constituted only 6.4 percent of the basin (Curtis, 1973, p. 147). Effects of mining in arid to semiarid climates are cause for special concern (National Academy of Science, 1974). Damage from erosion may be great in such areas because the natural regrowth of stabilizing vegetation is inhibited and surficial discharge typically is "flashy," the result of infrequent yet intense rainstorms.

Coal mining affects erosion, sedimentation, and runoff in many ways. Excavation and placement of spoil generally roughen, lengthen, and steepen slopes (fig. 26). These activities also destroy vegetative groundcover and disturb pedogenic horizons. Acids and other phytotoxic substances that are produced when mined spoil weathers may prevent the reestablishment of plants capable of stabilizing loose sediment (Berg, 1965). Such effects accelerate incision and unchanneled or sheetflood erosion. Mounds of unconsolidated, unvegetated spoil are especially vulnerable to denudation and slope failure and contribute a large percentage of the sediment transported from mine sites (Curtis, 1973, p. 147).

Redistributed sediment accumulates on gentle, upland slopes and in streams and reservoirs. This sediment may alter the pattern, volume, and rate of drainage. Runoff is increased by steepening and devegetating slopes (Curtis, 1973), thereby reducing infiltration and recharge. Conversely, the roughening and lengthening of slopes may enhance opportunities for absorption of water (Merz and Finn, 1951), thus reducing runoff. The retentive capacity of spoil mounds is particularly great, such that they may constitute local, perched aquifers (Agnew and Corbett, 1973). Water also may be impounded on spoil mounds (fig.

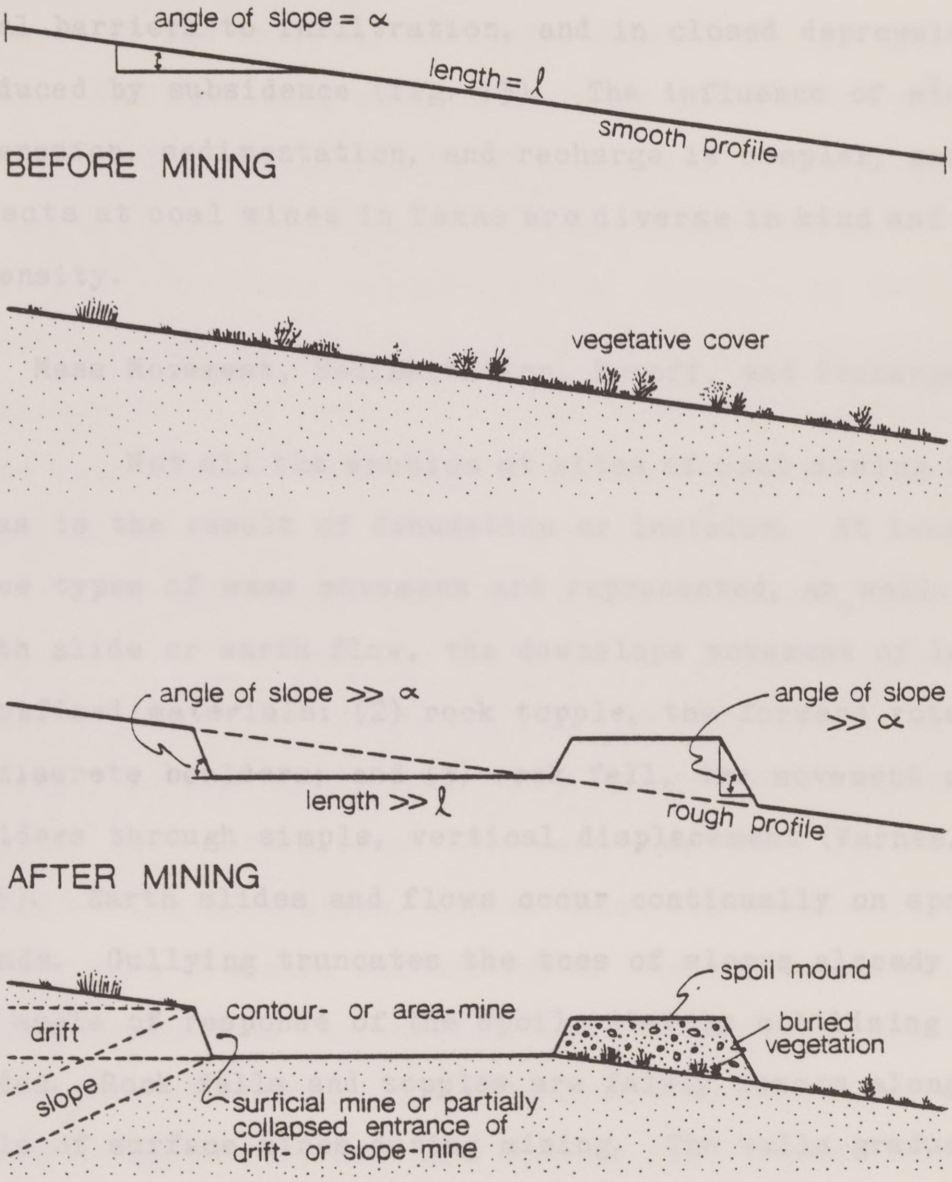


Figure 26. Effects of excavation and placement of spoil on slopes at mine sites. Effects include devegetation and lengthening, roughening, and steepening slopes.

25) and abandoned surface mines (fig. 9) where there are local barriers to infiltration, and in closed depressions produced by subsidence (fig. 13). The influence of mining on erosion, sedimentation, and recharge is complex, and effects at coal mines in Texas are diverse in kind and intensity.

Mass Movement, Sedimentation, Runoff, and Recharge

Not all the erosion at sites of coal mining in Texas is the result of denudation or incision. At least three types of mass movement are represented, as well: (1) earth slide or earth flow, the downslope movement of loose, unconfined materials; (2) rock topple, the forward rotation of discrete boulders; and (3) rock fall, the movement of boulders through simple, vertical displacement (Varnes, 1975). Earth slides and flows occur continually on spoil mounds. Gullying truncates the toes of slopes already at the angle of response of the spoil, thereby mobilizing small slides. Rock falls and topples are fairly common along the walls of surface mines during mining. The walls gradually attain an equilibrium profile unless repeatedly over-steepened.

At a site in Montague County (M/SL-4-1), spoil had been placed on a steep slope (20 percent gradient) just above the entrance of a drift mine. An apparently sudden collapse of the entryway initiated failure of the spoil mound. The resulting slide of perhaps 250 m^3 (327 yd^3) of earth buried several, small oak trees, one of which survived and is now 0.22 m (0.75 ft) in diameter and highly contorted (fig. 27). Continued collapse at the entrance of this mine caused a thick, overlying bed of indurated, Lower Cretaceous conglomerate to be undercut. Large blocks of conglomerate broke free along preexisting joints and toppled onto the slope below.

Gradual sedimentation is a more common occurrence at mine sites. Slopes may be buried (fig. 20) and streams choked with debris. Suspended particles may reduce water quality. Several small reservoirs in North-Central, East-Central, and eastern Texas have been completely filled with sediment from mine sites, and at least two reservoirs subsequently were breached and destroyed. As the capacity of small impoundments decreases, water in retention will lap ever higher on the dam. The capacity of an impoundment at mine site Ea/CN-2-3, Eastland County, was exceeded during a heavy rainstorm in the summer of 1979 (fig. 28) causing the water to spill over and breach the masonry-reinforced earthen dam (Finley and others, 1979, p. 28). Despite emergency efforts to save the reservoir (remains of sand

Figure 27. Effects of an earth slide at mine-site number M/SL-4-1, Montague County, Texas, 1979. The small oak tree shown was contorted by the flow but survived.

Figure 28. Failed earthen dam just below mine-site number Ea/CN-2-3, Eastland County, Texas, 1979.

bags still were in place at the time of inspection) the dam failed quickly. The sudden outrush of water and debris carved a deep channel below the dam, completely filled a second, small reservoir with sediment, and spread a thick layer of sand and clay over the banks of the stream as far as 1 km (0.6 mi) downstream. An almost identical incident had occurred only a year earlier below mine site Ba/Ba-4-10, Bastrop County. Both reservoirs were about 2 ha (5 ac) in area.

The redistribution of significant quantities of sediment in a drainage basin could be reflected in the volume and rate of runoff. A surface that is roughened and lengthened by excavations, spoil mounds, and subsidence basins will not convey overland discharge as efficiently as it did prior to mining. But factors that retard runoff may be more than offset at some sites by the loss of vegetation, steepening of slopes, and diversion of runoff into shorter paths of drainage. At mine sites, the nature of effects on runoff can be inferred from the extent of erosion. Lane (1955) demonstrated a qualitative relationship between sediment-yield (Qs) and discharge (Qw), such that

$$Qs\ D \propto Qw\ S,$$

where D is the mean diameter of transported particles and S is the slope. Factor D is a measure of competence but the size of available sediment is restricted at most mine sites in the state with sand and clay predominating. An increase in sediment yield can be accounted only by a proportional increase on the right side of Lane's equation. Because gradient and discharge are closely associated, runoff will increase even if the initial effect is to steepen the slope. Therefore, high rates of erosion at most mine sites are the result of adjustments of the hydrologic regime to modifications of the environment. Unfortunately there are no prior records of discharge for any of these sites or the low-order streams into which they drain, making it difficult to quantify effects on erosion. Yet there are qualitative indications that runoff increased overall.

Unless there has been a substantial change in the amount of water stored at a site an increase in runoff generally denotes a decrease in recharge. Hydrogeologic effects of mining coal in Texas have been discussed by several investigators but none have attempted to define this evident change in the ratio of recharge to runoff. Several factors complicate this relation. Water is retained at mine sites in impoundments and in intergranular storage within spoil mounds. Open pits (at surface mines), subsidence basins, and depressions on and between spoil mounds function as impoundments. Spoil mounds (fig. 29) consisting of porous media and adsorptive clays, have huge capacities for

Figure 29. Oblique aerial photograph of large spoil mound at mine-site number Er/G-2-56, Erath County, Texas, 1979. Photograph by William Hupp, Texas Department of Water Resources (used with permission).

storing vadose and perched ground water. During this study, standing water was observed at several sites more than two weeks after the most recent rains (fig. 25). Discharge from spoil mounds evidently had supplemented the pluvial waters. Both surficial storage and runoff appear to have increased after mining, at least locally, and only a small fraction of the precipitation reaches the water table.

Recharge at most mine sites (except those in parts of the outcrop of the Wilcox Group) probably was small prior to mining because of the same barriers to infiltration that protected the coal from oxidation. In addition, a mined area is negligibly small in terms of its percentage of the total contributions to a major aquifer. Even if recharge is, in fact, reduced at some mine sites the effect on supplies of ground water unquestionably is minimal and of interest mainly as a potential indicator of increased runoff. However, the mine itself may have a residual effect on the piezometric surface in its vicinity. The mine may extend beneath the local water table or penetrate a confined aquifer. An estimate of the size of the affected area can be obtained from a relation defined by McWhorter and Rowe (1976):

$$r = (R/c)|(Ko - K)/(Ko + Ki)|^{1/2}$$

where

r = distance from the center of the mined area to points at which the piezometric head is lower than it was prior to mining by an amount corresponding to the arbitrary factor c;

R = radius of a circle the area of which is equal to that of the mine;

c = ratio of the difference in head before and after mining to the head before mining, at a distance r from the center of the mined area;

Ko = hydraulic conductivity of the aquifer outside the mined area;

Ki = hydraulic conductivity of the aquifer within the mined area.

The aquifer is assumed to be otherwise homogeneous.

If Ko and Ki are unknown the maximum distance r can be determined by setting Ki = 0 or ∞ at which

$$r = R/c.$$

If we are interested in knowing the distance at which the piezometric head differs by ten percent then c = 0.1 and r = 3R. When c = 0.01, r = 10R. For a mine covering 1 km^2, R = 0.56 km. Although we may know very little about the aquifer we can obtain an estimate of the radius of the cone of depression around the mine that is probably at least in the order of magnitude of the true value. Of course, more powerful hydrologic models are available (see discussion by Dutton, 1982).

In humid regions, the loss of head around an undrained surface mine of moderate size may be imperceptible. A mine located in the outcrop (area of recharge) of the Wilcox Group in northeastern Texas illustrates this effect. The mine, at site Hp/SSe-1-2, Hopkins County, was more than 18m (60 ft) deep prior to reclamation in 1981. The water table was about 7.6m (25 ft) deep. Seepage through the walls of the mine was extremely rapid and water was pumped continuously during mining. A series of shallow wells around the perimeter of the mine (fig. 8) were installed and operated in a further attempt to reduce phreatic inflow. If all pumps were operated lignite could be mined without difficulty. Yet in spite of these significant withdrawals the level of water in a shallow well less than 100 m (330 ft) from the mine was unaffected. Effects in western, southern, and north-central areas of the state, where precipitation and transmissivity are much lower, might be more severe.

Quantitative Assessment of Erosion and Deposition

The current investigation has produced measurements or quantitative estimates of erosion and deposition at numerous mine sites. This study employed three methods for determining the amounts and rates of redistribution of sediment: (1) direct monitoring of deposition or denudation over a finite period; (2) measurement of the gross erosion or deposition since curtailment of mining; and (3) estimation of the progressive loss or addition of sediment through interpretation of aerial photographs of differing age. Two or even all three of these methods were applied at some sites. Data from detailed studies at selected sites were extrapolated semiquantitively (appendix C) to sites visited only briefly or depicted on only one series of aerial photographs.

The selection of a site for detailed assessment of erosion and deposition was based on: (1) accessibility for monitoring and other measurements; (2) adequacy of local historical information regarding mining; (3) coverage under one or more series of aerial photographs; and (4) an indication that the observed impact had resulted solely from the effects of mining. Whereas quantitative data were obtained at only a limited number of mines relative impact was assessed at all sites. The effort to quantify effects in selected areas also served to calibrate the qualitative observations made elsewhere.

Monitoring

Local losses of sediment were carefully monitored at a site in East-Central Texas. A set of ten monitoring devices was installed on the spoil mound at mine site Ba/Ba-4-9 near Phelan, Bastrop County (fig. 30) on April 29, 1982. Each monitor used in this study consisted of a large metal washer through which a nail 25 cm (10 inches) long had been passed. The inside diameter of the washer was only slightly larger than the diameter of the shank of the nail, so that the washer could not pass over the nail's head but could move freely along its shank. The nail was long enough to be driven vertically into the ground to a solid position with its head still several centimeters above the surface. The washer rested on the ground. Erosion removed sediment from beneath or around the washer which then dropped by a distance corresponding to the thickness of sediment removed. Deposition at the monitor would partly or completely bury the washer to a corresponding depth. Thus when the distance from the nail's head to the ground or to the washer is compared to the distance measured when the pin was installed the net change, either deposition or erosion, can be determined directly. A calibrated rain collector positioned within the field of monitors provided a cumulative record of

Figure 30. Oblique aerial photograph of spoil mound at mine-site number Ba/Ba-4-9, near Phelan, Bastrop County, 1982. Photograph by R. C. Wynn and H. W. Schoellkopf, Jr., Dallas (used with permission).

the precipitation that had been mobilized the sediment. This method for monitoring erosion and deposition originally was described by Leopold and others (1966, p. 202) and has been used successfully (with slight modification) in Texas by Finley and Gustavson (1980, p. 38)

Table 6 compares the initial measurements, when the ten monitors were installed, with measurements taken two days later. Exactly 5 cm (2.0 inches) of rain had fallen during that two-day period. These measurements are a reasonable estimate of the movement of sediment on the spoil mound in response to rains of a specific intensity. The maximum erosion observed at the site was 0.4 cm (0.16 inch), in a gully on a steep flank of the mound. The arithmetic mean of the measurements at all ten monitors was 0.194 cm (0.076 inch). The mean is an indication of the general redistribution of sediment on disected and undissected slopes of differing aspect, gradient, and substrate. Deposition occurred at only one monitor which is an insufficient basis from which to draw conclusions or calculate a mean. However, monitoring provided the most direct indication of rates of erosion obtained at any site investigated during this study.

Unfortunately, soon after installation the monitors had to be removed when cattle were allowed to enter the area in which the mine is located. One of the monitors

Table 6. Data from direct monitoring of the movement of sediment on a spoil mound at mine site number Ba/Ba-4-9, Phelan, Bastrop County, Texas

All measurements in centimeters from top of head of nail (monitor).

Pin number	Installation date: April 29, 1982 Pin to washer	Installation date: April 29, 1982 Pin to ground	Monitoring date: April 31, 1982 Pin to washer	Monitoring date: April 31, 1982 Pin to ground[1]	Erosion	Deposition
B7	13.7	13.8	13.7	13.9	0.1	0.0
XX	8.8	9.6	9.1	10.0	0.3	0.0
O	11.6	15.3	11.6	15.0	0.0	0.3
E6	10.0	10.4	10.3	10.7	0.3	0.0
H8	11.4	12.0	11.4	12.0	0.0	0.0
C	9.6	9.8	9.45	10.1	0.15	0.0
U	9.6	10.4	9.3	10.9	0.3	0.0
C5	12.0	12.6	12.2	12.6	0.2	0.0
S	15.6	15.7	--[2]	--[2]	---	---
I4	8.3	8.7	7.9	9.2	0.4	0.0
Mean	--	--	--	--	0.194	N.R.
Maximum	--	--	--	--	0.4	N.R.

[1]Erosion inferred from this measurement if: (1) washer clearly had been undercut but was held in place by sediment on the upslope side of the nail or (2) washer had protected the sediment immediately beneath it while erosion occurred around the washer, forming a washer-capped "hoodoo."

[2]Measurements deleted because monitor was disturbed by cattle.

N.R. Values not representative because data are insufficient.

evidently was disturbed by cattle during the first two days of monitoring. For this reason and because the animals themselves were capable of enhancing erosion, the monitoring effort was abandoned at this site. And because the rain gauge used in this study must be read immediately after each shower the site of monitoring had to be very near Austin. No otherwise suitable location provided the necessary ease of access, and so the monitors were not reinstalled.

Table 7 and figure 31 include data from this brief period of monitoring. Because the data were collected after only two days, projection of these results over an entire year is meaningful only if consideration is given to the amount of rainfall that produced the observed erosion. Storms producing rainfall of a given intensity occur with predictable frequency. However, all rains cause at least some redistribution of sediment at the site. A rough estimate of erosion can be obtained by assuming the ratios of the mean and maximum erosion to precipitation are constant at a given site over the short term. The cumulative erosion (mean and maximum) over a year then is calculated in the following manner.

$E_a = (E/P_e) \times (P_a)$ where

Table 7. Erosion at selected mine sites, and corresponding erosional rates.

Site (number)	(X_i) Time of abandonment (yr before 1983)	Erosion (Y_i) sheetflood and rill (m)	Erosion (Y_i) gully and streambank (m)	Erosional rate sheetflood and rill (m/yr)	Erosional rate gully and streambank (m/yr)
Hp/Y-3-1	4	(1) 0.33[1]	(2) 0.5	(1) 0.0825	(2) 0.1250
	4	---	(3) 4.5*	---	(3) 1.1250*
Hp/SSe-1-2	4	(4) 0.5*	(5) 0.5	(4) 0.1250*	(5) 0.1250
Ba/Ba-4-9					
(mean)	10	(6) 0.355[2,3,4]		(6) 0.0355[2,3,4]	
(maximum)	10	---	(7) 0.731[2]	---	(7) 0.0731[2]
Y/N-2-7	36	(8) 0.5	---	(8) 0.0139	---
J/LC-4-21	38	---	(a) 1.5	---	(9) 0.0395
M/BM-1-4					
(mean)	58	(10) 0.75[3]	---	(10) 0.0129[3]	---
(maximum)	58	(11) 1.0	(12) 2.75	(11) 0.0172	(12) 0.0474
C/FF-4-14	63	(13) 1.25	(14) 2.25	(13) 0.0198	(14) 0.0357
J/LC-4-41	63	---	(15) 3.0	---	(15) 0.0476
Er/G-2-63	69	(16) 1.5	(17) 3.0	(16) 0.0217	(17) 0.0435

*Erosion enhanced by concentrated or diverted discharge. Value not treated statistically.

[1]Numbers in parentheses correspond to points shown in figures 31, 35, and 36.

[2]Results of temporary monitoring projected over 10 years.

[3]Arithmetic mean of discrete measurements (ten measurements at each site)

[4]Combined effects of channeled and unchanneled discharge.

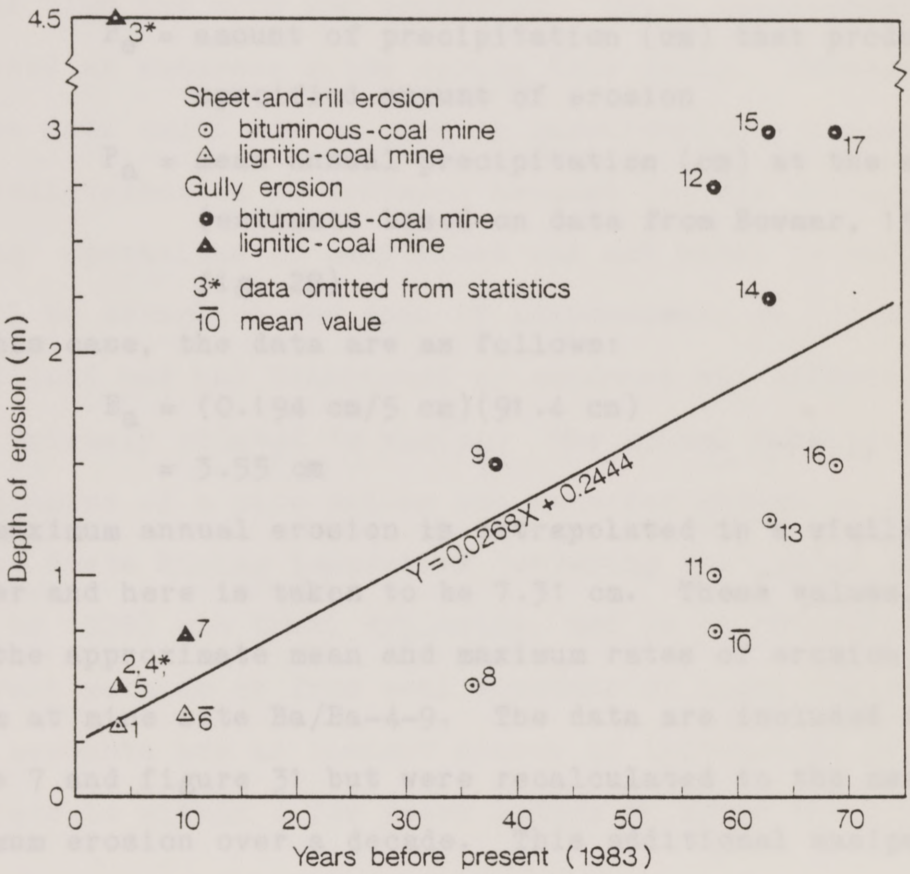


Figure 31. Least-squares fit to erosional data in table 7 (see also table 8). Mining at sites number Hp/SSe-1-2 and Hp/Y-3-1 actually ended in 1976 and both sites were reclaimed in 1980.

E_a = mean, annual erosion (cm) at the site

E = mean of all measurement of erosion (cm) resulting from a specified amount of precipitation (single shower)

P_e = amount of precipitation (cm) that produces a specified amount of erosion

P_a = mean annual precipitation (cm) at the site (estimate based on data from Bowmar, 1983, fig. 28)

In this case, the data are as follows:

$$E_a = (0.194 \text{ cm}/5 \text{ cm})(91.4 \text{ cm})$$
$$= 3.55 \text{ cm}$$

The maximum annual erosion is extrapolated in a similar manner and here is taken to be 7.31 cm. These values, then, are the approximate mean and maximum rates of erosion per annum at mine site Ba/Ba-4-9. The data are included in table 7 and figure 31 but were recalculated to the mean and maximum erosion over a decade. This additional manipulation is merely to facilitate graphic representation of the data. The mean value reflects the combined effects of erosion by sheetflood, rills, and gullies. The maximum erosion occurred in a gully.

Gross Measurements

Gross erosion and deposition are measured relative to a fixed local datum assumed to represent the ground level at the time the mine was abandoned. Gross measurements were obtained at numerous sites during this study. However, much of the data could not be used in quantitatively assessing the redistribution of sediment because (1) the history of mining operations at many sites was not known in sufficient detail to establish the date of abandonment; or (2) subsequent land use had diminished or enhanced the effects that were uniquely related to mining. The actual date (year) of abandonment of a mine seldom was recorded except in reports of the State Mining Inspectors (covering the period from 1909 to 1928) and thus, typically, had to be determined by indirect methods or from oral accounts of local residents. Such accounts are an inexact source of information probably accurate to within a few years before or after the actual date.

In practice, a gross measurement generally reflects changes relative to a datum such as the footing of a structure, the origin of which can be dated only approximately. The position of this point of reference relative to the ground at the cessation of mining also must be approximated. Certainly some erosion and deposition occurred while sites were being mined. However, values obtained by this procedure appear to be representative. Normal operations at the mine likely overwhelmed erosional and depositional effects as quickly as they occurred. Therefore the majority of the change in ground level probably was felt after earth-moving activities at the mine had ceased. Also, the period since abandonment generally is much longer than the period of mining.

After a site had been abandoned in terms of the mining operation other land uses continued. Those uses that could most readily obscure the intrinsic effects of mining include: removal of material from the site for use as fill or raw stock for making bricks; regrading the site for cultivation or creation of a small reservoir ("stock tank"); and maintenance of a large concentration of livestock at the site. Subsequent land use probably has affected rates of erosion and deposition at most mine sites. Recognition of the effects attributable to mining alone can be very difficult and generally requires careful inspection of the site.

Inferred rates of erosion or deposition were derived from measurements of either the depth of gullies, rills, and denuded, unchanneled slopes or the thickness of accumulated sediment. The loss or addition of soil or other material was measured relative to a stable structure or surface that had been relatively protected in some way from erosion or burial. This datum might have been a line of discoloration or a break in the surficial texture of a structural footing, corresponding to the original ground level. Secondarily, a stable slope on a spoil mound could be a suitable datum, particularly if that part of the mound was armored with coarse sediment or was screened from rain beneath the branches of trees. When the datum was a protected surface on a spoil mound the determined rate of erosion is a minimum.

The depths of gullies were measured at selected mine sites in Coleman, Erath, Hopkins, Jack, and Montague Counties (table 7; fig. 31). The year in which mining was discontinued at each of these sites is indicated in figure 31 as years before 1983. Each value is considered representative of erosion by gullying at the site as a whole. The depths reported generally were the maxima observed, but were not gross anomalies except as noted. The exception is a measurement at mine site Hp/Y-3-1 in Hopkins County. Spoil from this surface mine had been placed along the contour across a swale that drained an area of approximately 0.5 km^2 (0.2 mi^2) on an adjacent upland. Normally, mines are sited in such a way as to minimize the entry of runoff, but at this site, drainage was concentrated at the site at a point where the spoil was 4.5 m (15 ft) thick. The entire thickness of spoil was breached by runoff, producing a gully 4.5 m (15 ft) deep and as much as 19 m (60 ft) wide (fig. 32) within 4 years after mining began and ended in 1976 (unpublished records, Railroad Commision of Texas, Surface Mining and Reclamation Division). The site was reclaimed in 1980. This measurement is included in table 7 and figure 31 but was not used in statistical analyses. Measurements of erosion in other parts of this site are included in the regressional statistics.

Measurements of erosion in rills and on sheet-flooded surfaces were recorded at sites in Coleman, Erath, Hopkins, Montague, and Young Counties (fig. 33). These measurements are representative of unchanneled and micro-channeled erosion across the respective sites, although all are local maxima. A large structure at mine site M/BM-1-4 was supported on 12 concrete footings poured in place (fig. 34). The sheetflood erosion at each of these footings was measured from a line around each footing that represented the ground level when the concrete was poured, probably before 1920. The mine was abandoned in or about 1925 (Finley and others, 1979, p. 178). Although erosion may have begun before abandonment of the mine it is equally possible that additional material could have covered the

Figure 32. Deep gully at mine-site number Hp/Y-3-1, Hopkins County, Texas, 1980. The gully is cutting through 3 m of spoil material.

(a)

(b)

Figure 33. Effects of sheetflood erosion at mine-site number C/FF-4-14, Coleman County, Texas, from 1916 to 1979.

(a) Site as it appeared in 1916 when the mine was being operated intermittently. Photograph reproduced from an original owned by Linnie Box, Rockwood, Texas (used with permission).

(b) Site as it appeared in 1979 from same position.

Figure 34. Effects of sheetflood erosion and gullying at mine-site number M/BM-1-4, Montague County, Texas, from 1925 to 1979.

original surface until erosion began sometime later. For the present purpose, erosion is assumed to indicate removal of sediment from the former surface indicated on the footings, and to have begun in the year the mine was abandoned. The mean calculated from these 12 measurements is included along with the maximum value from this set (table 7).

One anomalous value is included among the data for sheetflood and rill erosion but was not used in generating statistics. This measurement was recorded at the site of an abandoned surface mine, number Hp/SSe-1-2, in Hopkins County. Although part of the observed loss of sediment resulted from normal runoff, erosion was greatly enhanced by the discharge of ground water pumped from the mine and from shallow wells in the overburden surrounding the mine (fig. 8). The mine was approximately 20 m (65 ft) deep and received a continuous discharge of ground water through the highwalls. Water was pumped from the mine onto a broad slope draining into a nearby stream. This drainage accelerated the development of preexisting gullies (identified on aerial photographs predating the opening of the mine) and spread a thick blanket of sediment across the slope and into the adjacent channel. The extensive redistribution of sediment at this site is particularly noteworthy because the mine operated for only a few months. Yet sheetflood erosion rapidly removed up to 0.5 m of loose sand from the toe of a large spoil mound covering part of the slope near the mine. In addition, a section of fence about 1 m (3.3 ft) high and 20 m (65 ft) long was completely buried. These measurements are noted here simply for comparative purposes. They are extreme examples of the erosion and deposition that may occur when factors are most conducive.

Interpretation of Aerial Photographs

Vertical and oblique (hand-held) aerial photographs and direct aerial observations were invaluable in this investigation of erosion and deposition at mine sites. Photographic interpretation particularly complimented the field studies by revealing the areal extent and progression of effects noted on the ground. Evaluations based on the appearance of buried or eroded surfaces in photographs were combined with data obtained through monitoring and measurement of gross erosion and deposition at these sites. In this way the interpretation of imagery was effectively calibrated, permitting an expansion of the number of sites for which a semiquantitative assessment of erosion could be made.

Appendix C summarizes the results of this analysis. The area affected by erosion at most mine sites was measured on aerial photographs. The severity of effects was determined at the same time using correlative data from surveys on the ground. Where confirmatory observations were absent, the photographic interpretations generally were conservative such that the estimated severity of erosion or deposition locally may be understated. The scale, resolution, and contrast of many of the aerial photographs available for use in this study were inadequate for a detailed review of impact. But where effects were evident they were characterized as completely as the images would permit.

Photointerpretive assessments of erosion and deposition usually involved the use of both historical and recent aerial photographs. If a site had been photographed more than once the images with earliest and latest vintage were compared and apparent changes noted. The condition of some sites has improved through time whereas that of others has deteriorated markedly. It was not possible at every site to determine whether worsening erosion, deposition, or other problems were solely in the aftermath of mining or had been exacerbated by other land uses. Unless there was clear evidence (from photointerpretation or field studies) that adverse effects had resulted from subsequent use the present condition of each site was assumed to have resulted from mining.

Analysis of Quantitative Data

Data collected during this study represent the effects of erosion in different regions, acting over periods of unequal length. The surficial gradient, vegetative cover, texture and consolidation of the substrate, and type of erosion (whether resulting from channeled or unchanneled discharge) varied both within and among sites. Measurements shown in table 7 include local maxima as well as means of several discrete observations at given locations.

It was not clear at the outset what relation these measurements might have to one another or to rates of erosion noted elsewhere. For this reason, a few simple statistical manipulations of the data were performed to express their relations mathematically. This provided a method for comparing and testing the relevance of these isolated observations, and a predictive technique for projecting effects through time. Although the data compose a small set (n = 15), each point appears to accurately represent the erosion observed at a given site. The history of mining and date (year) of abandonment of each site were known and effects of subsequent land use were negligible.

The data employed in this analysis (table 7) are displayed graphically in figure 31. Years before present (1983) constitute the abscissa of this Cartesian graph. Depths of erosion (in meters) form the ordinate. Denudation caused by sheetflooding and discharge through rills is indicated by one symbol, whereas losses attributable to erosion within gullies and streams are denoted by another. The points are scattered but from inspection of figure 31 the data clearly consist of two families corresponding to the two symbols. In general, erosion increases through time but at an almost constant or slightly declining rate. Yet even after 69 years (observations at mine site Er/G-2-63), there is no indication that erosion has abated completely.

Regression of the data confirms these preliminary observations. Table 8 summarizes the linear regression and the "least-squares" fit to the data is shown in figure 31. The slope of the least-squares line is the weighted-mean rate of erosion caused by channeled and unchanneled discharge. That rate, 0.0268 m/yr or 2.68 cm/yr (1.06 in/yr), is extremely high, although it is much lower than the arithmetic mean of all calculated rates, 4.63 cm/yr (1.82 in/yr). The seemingly large value for the y-intercept in figure 31 is somewhat puzzling. Logically, the least-squares line should pass through the origin (point 0, 0 in fig. 31) but it does not.

Table 8 . Functional relationship between erosion and time of abandonment of a mine site (linear regression of data in Table 7 .).

		Mean erosion[1]		Maximum erosion[2]	
s	all points (m)	(A) sheetflood and rill (m)	(B) gully and stream (m)	(C) sheetflood and rill (m)	(D) gully and stream (m)
ΣX	607.	240.	251.	230.	309.
ΣY	19.916	4.685	11.105	4.580	14.231
ΣXY	1,072.18	248.62	602.30	259.57	765.56
ΣX^2	34,509.	13,506.	14,275	13,406.	17,639.
$(\Sigma X)^2$	368,449.	57,600.	63,001.	52,900.	95,481.
n	15.	6.	7.	5.	8.
b	0.0268	0.0157	0.0387	0.0173	0.0378
a	0.2444	0.1539	0.1990	0.1202	0.3169
$\bar{X}$	40.4667				
$\bar{Y}$	1.3277				
ΣY^2	39.7693				
$(\Sigma Y)^2$	396.6471				

	Erosional rates[3]		
	sheetflood and rill (m/yr)	gully and stream (m/yr)	all points (m/yr)
$\Sigma(Y/X)$	0.20350	0.57230	0.74030
n	7.	9.	15.
$\frac{\Sigma(Y/X)}{n}$	0.02907	0.06359	0.04627

[1]Erosion at all sites including mean erosion at mine sites Ba/Ba-4-9 and M/BM-1-4.

[2]Erosion at all sites including maximum erosion at mine sites Ba/Ba-4-9 and M/BM-1-4.

[3]Mean rates of erosion calculated from erosional rates at individual sites (table 7).

To determine whether the calculated rate and y-intercept are representative a series of tests were performed. These are summarized in table 9 using the notation of Sokal and Rohlf (1981, p. 473, 474). The tests for the coefficient of regression (slope of the least-squares line) include: (1) standard error; (2) significance; and (3) 95-percent limits of confidence. Other tests performed on the data were determinations of the standard errors of both the y-intercept and the mean of all measurements of erosion.

The coefficient of regression is 0.0268 (table 8). Its standard error is equal to one standard deviation or 0.00692 (table 9). This indicates that within the limits of approximately 68-percent confidence, the slope of the least-squares line through the population of erosional data (that is, the weighted-mean rate of erosion) is 0.0268 $\pm$ 0.00692 or between 0.01988 and 0.03372. This is a reasonable range in view of the fact that the set of all erosional data includes measurements of effects of sheetflooding and discharge through rills as well as discharge through gullies and streams. Within the limits of 95-percent confidence (slightly less than two standard deviations), the range is 0.01184 to 0.04176 (table 9). Despite the width of this range the coefficient of regression appears to be a legitimate approximation of the general rate of erosion at mine

Table 9. Tests of coefficient of regression and y-intercept. Notation follows Sokal and Rohlf (1981, p. 473, 474).

Standard error of coefficient of regression

$$\Sigma_x{}^2 = \Sigma X^2 - (\Sigma X)^2/n = 9,945.733$$

$$\Sigma_y{}^2 = \Sigma Y^2 - (\Sigma Y)^2/n = 13.326$$

$$\Sigma xy = \Sigma XY - (\Sigma X)(\Sigma Y)/n = 266.250$$

$$(\Sigma xy)^2 = 70,899.066$$

$$s_b = (s^2{}_{y\cdot x}/\Sigma x^2)^{\frac{1}{2}} = [(\Sigma d^2{}_{y\cdot x}/n-2)\ (\Sigma x^2)^{-1}]^{\frac{1}{2}}$$

$$= \left| \frac{\Sigma y^2 - (\Sigma xy)^2/\Sigma x^2}{(n-2)\ (\Sigma x^2)} \right|^{\frac{1}{2}} = 0.00692$$

Testing -- significance of coefficient of regression

$$t_s = (b - o)/s_b = (0.0268 - 0.00)/0.00692 = 3.87283$$

$$t_{.001[13]} = 4.221$$

$$t_{.01[13]} = 3.012$$

$$t_{.01[13]} > ts > t_{.001[13]}$$

$$0.01 > P > 0.001$$

Limits of 95-percent confidence for coefficient of regression

$$t_{.05[13]}\ s_b = 0.01496$$

$$b + t_{.05[13]} = 0.04176 = L_1$$

$$b - t_{.05[13]} = 0.01184 = L_2$$

Standard error of the sampled mean $\overline{Y}$ (at $\overline{X}$)

$$s_{\overline{y}} = (s^2_{y.x}/n)^{\frac{1}{2}} = 0.17829$$

Expected Y at $\overline{X}$

$$Y = b\overline{X} + a = 1.32890$$

Standard error of y-intercept

$$S_a = [S^2_{y.x}(1/n + \overline{X}^2/\Sigma x^2)]^{\frac{1}{2}} = 0.33210$$

sites. Even the upper end of the range is still far below the arithmetic-mean rate of erosion, 0.04627 m/yr, a much less refined estimate of the overall rate. Note that in table 7 the mean rate of erosion calculated from observations at mine site Ba/Ba-4-9 is listed under both columns of erosional rates. Both entries were included in the calculation of the arithmetic-mean rate. If the mean rate at Ba/Ba-4-9 is omitted, the mean for all remaining sites is 0.04755 m/yr, an even larger value well outside the limits of 95-percent confidence.

The scalar disparity of the axes of figure 31 is great: the full range of plotted values falls within 70 units along the abscissa but only 5 units along the ordinate. Therefore the slope of the least-squares line is small. This is merely an artifact of the construction of the graph but it might conceivably have affected the sensitivity of the tests. To test the significance of the coefficient of regression a null hypothesis was stated and evaluated. The null hypothesis states that the slope of the line was not significantly different from zero. (The formal statement of this hypothesis would be: Could the value for the coefficient of regression that was calculated from the existing erosional data have been obtained from an unrepresentative sample of a larger population whose parametric coefficient of regression was zero?). Since the rate of erosion logically could not be zero, acceptance of the null hypothesis on the basis of statistical significance would be a fallacy indicative of insensitive testing. But in fact, the test of significance indicates the probability that the null hypothesis is correct is less than one percent ($0.01 > P > 0.001$), and the hypothesis is rejected. This conclusion relieved much of the concern over the sensitivity of the tests.

Two other tests provided confirmatory indications. The standard error of the mean of tabulated depths of erosion (at the mean number of years before present over which erosion occurred, $\bar{X}$) is about 0.1783. The mean depth of erosion for the period of record (69 years) is 1.3277 m. Substituting the value of X into the regressional relation yields a predicted mean depth of 1.3289 m, which equals the mean value of the individual depths allowing for discrepancies owing to independent rounding. Using the predicted mean depth, the range of values within one standard deviation is 1.1506 to 1.5072 m after approximately 40 years of erosion. This may be a more telling indication of the rate of erosion than is the range of values for the coefficient of regression within the 95-percent limits of confidence.

Yet from inspection of figure 31 it is clear that the mean depth reflects the seeming bimodal distribution of the data.

Of greater concern, at least initially, was the apparently high value of the y-intercept in the regression (table 8). The calculated value is 0.2444 m. As stated previously, the least-squares line logically would pass through the origin of the graph of plotted erosional data (fig. 31). To test this discrepancy the standard error of the y-intercept was calculated and found to be 0.33210 m. In fact, the value obtained through regression is substantially less than the standard error or one standard deviation. Therefore the discrepancy is easily tolerated and largely accounted by the regression.

Whereas the regression provides a useful assessment of the complete set of erosional data there are several indications that the set consists of two or more discrete families of data. Figure 35 separates the data graphically and table 8 presents separate linear regressions of the data within each family. The erosional rates obtained through these calculations may be more representative of the denudation and incision at these mine sites than is the value from regression of the data treated as a single set. However, the number of points in each family was necessarily small, limiting the practicability of additional

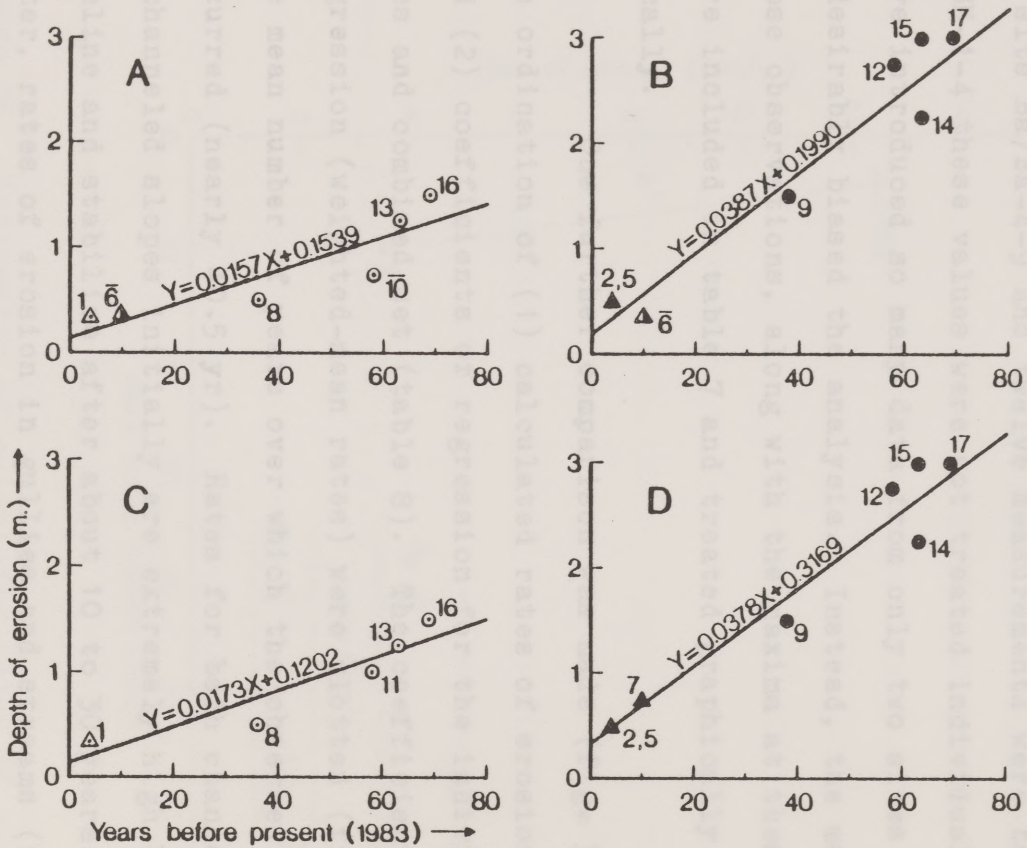


Figure 35. Least squares lines fit to families of erosional data in table 8. All symbols as in fig. 31.

analyses. The complete set of data was intended to provide an indication of erosion in a variety of settings and under different conditions. Although ten observations were made at site Ba/Ba-4-9 and twelve measurements were taken at site M/BM-1-4 these values were not treated individually. To have introduced so many data from only two sites might have undesirably biased the analysis. Instead, the means of these observations, along with the maxima at these sites, were included in table 7 and treated graphically and statistically.

One further comparison was made (fig. 36), through the ordination of (1) calculated rates of erosion (table 7) and (2) coefficients of regression for the individual families and combined set (table 8). The coefficients of regression (weighted-mean rates) were plotted (fig. 36) at $\bar{X}$, the mean number of years over which the observed erosion occurred (nearly 40.5 yr). Rates for both channeled and unchanneled slopes initially are extremely high but seem to decline and stabilize after about 10 to 30 years. Thereafter, rates of erosion in gullies and streams (incision) are relatively constant but substantially greater than rates in rills and on unchanneled slopes (denudation). Although these conclusions tend to confirm observations in the field they conflict with another, intuitive assumption, that ero-

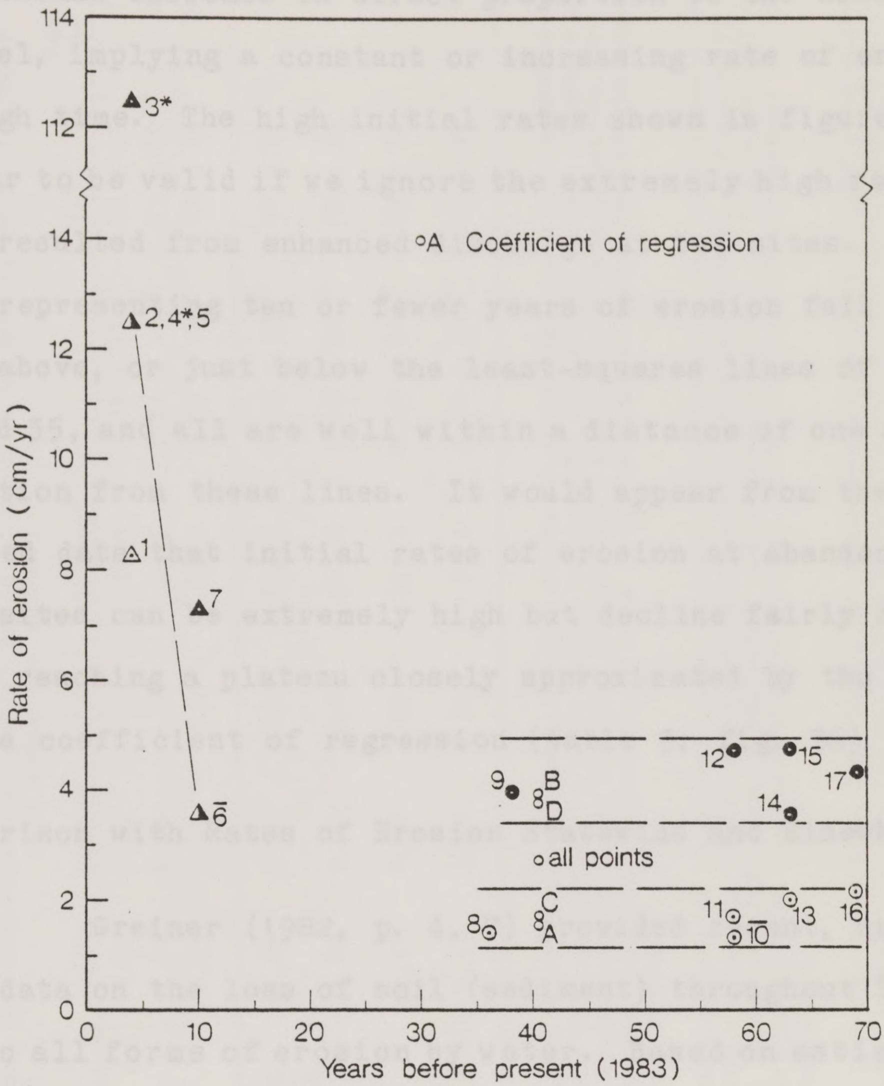


Figure 36. Ordination of calculated rates of erosion and coefficients of regression for individual families of erosional data. All symbols as in fig. 31 except as noted.

sion should increase in direct proportion to the size of the channel, implying a constant or increasing rate of erosion through time. The high initial rates shown in figure 36 appear to be valid if we ignore the extremely high rates that resulted from enhanced discharge at two sites. All data representing ten or fewer years of erosion fall on, just above, or just below the least-squares lines of figures 31 and 35, and all are well within a distance of one standard deviation from these lines. It would appear from these limited data that initial rates of erosion at abandoned mine sites can be extremely high but decline fairly rapidly until reaching a plateau closely approximated by the appropriate coefficient of regression (table 9; fig. 36).

Comparison with Rates of Erosion Statewide and Elsewhere

Greiner (1982, p. 4, 7) provided recent, quantitative data on the loss of soil (sediment) throughout Texas due to all forms of erosion by water. Based on estimates of losses above 300 fixed points of reference ("yield points") along streams within and bordering the state, the mean annual rate of erosion (other than eolian erosion) is 4.35 Mg/ha (1.94 ton/ac) (table 10). The highest rate above any yield point in the state is 17.25 Mg/ha (7.70 ton/ac). Assuming the density of sediment is approximately 1.28 Mg/m^3

Table 10. Summary and comparison of annual rates of erosion by moving water in Texas.[1] (All rates per annum.)

		Mg/ha	ton/ac	m^3/ha^3	ft^3/ac^3	m^4	ft^4	Percentage of total
Means of yield points	Sheet and rill	3.05	1.36	2.38	34.0	2.38×10^{-4}	7.81×10^{-4}	70.1
	Gully and streambank	1.30	0.58	1.01	14.5	1.01×10^{-4}	3.33×10^{-4}	29.9
	Total[5]	4.35	1.94	3.39	48.5	3.39×10^{-4}	1.11×10^{-3}	100.0
Maximum yield point	Total (yield point 30)	17.26	7.70	13.47	192.5	1.35×10^{-3}	4.42×10^{-3}	---
	Sheet and rill (yield point 115)	12.84	5.73	10.02	143.3	1.00×10^{-3}	3.29×10^{-3}	---
	Gully and streambank (yield point 227)	11.14	4.97	8.69	124.3	8.69×10^{-4}	2.85×10^{-3}	---
	Incremental sediment yield (yield point 39)[6]	6.77	3.02	5.28	75.5	5.28×10^{-4}	1.73×10^{-3}	---

[1]Basic data from Greiner (1982) except where noted. Units in which data were expressed by Greiner (1982) and others are here converted to more useful or readily comparable forms. Conversion introduces a small percentage of error because of rounding, but these errors generally are eliminated by calculating the tabulated values to no more than one decimal place beyond the appropriate number of significant figures.

[2]Yield points are fixed points of reference along streams. The location and significance of each of the 300 yield points figuring in the study are discussed by Greiner (1982). Erosion by water in that part of the drainage basin above each point was estimated by use of the universal soil-loss equation. Sediment loss in "noncontributing areas" (areas of internal drainage) is not included in these estimates.

[3]Volume of sediment loss per unit area determined by recalculating Greiner's (1982) estimate of the quantity of eroded sediment to an assumed sediment density of 1.2816 Mg/m^3 (80 lb/ft^3), the value accepted for general use by Leopold and others (1964, Appendix B). Other values for sediment density are given by the Soil Conservation Service (1968, p. 2-16 to 2-19; 1971, p. 10-11 to 10-13).

[4] Volume of sediment loss expressed as a uniform thickness of sediment removed from a unit area (ha or ac).

[5] The area from which this quantity of sediment is eroded annually is approximately 679,064 km^2 (262,187 mi^2), the total land area of the state.

[6] Incremental sediment yield is that amount of the sediment eroded above a yield point that is actually delivered to that point. Other sediment is trapped or detained within the basin above the yield point. Incremental sediment yield provides an indication of the lag response between sediment loss from a source area and conveyance of that sediment through the drainage network (see additional discussion by Greiner, 1982).

(80 lb/ft^3) (Leopold and others, 1964), the mean and maximum rates of denudation also can be stated as 3.39 m^3/ha (48.5 ft^3/ac) and 13.47 m^3/ha (192.5 ft^3/ac), respectively. Expressed another way, the volume of sediment eroded annually corresponds to a uniform layer of soil 0.34 mm (1.11 x 10^{-3} ft) thick over the entire state (excluding inland and coastal waters), an area of almost 680,000 km^2 (262,200 mi^2). Extrapolation of the mean rate in Texas over a millenium yields 0.34 m/1,000 yr (1.11 ft/1,000 yr) which is very nearly ten times the average rate (0.3 m or 1 ft per 9,120 yr) of denudation throughout the United States that was projected by Dole and Stabler (1909), and roughly one third the rate (about 1 m or 3 ft per 1,000 yr) estimated by Schumm, 1977.

Whereas the area affected by coal mining in Texas is less than 0.005 percent of the total land area (Caran, 1981), the annual rate of erosion at mine sites is almost 100 times greater than the mean rate statewide (tables 7 and 10). Thus, erosion at mine sites is a significant, if comparatively localized, environmental hazard in Texas.

Observed and calculated rates of erosion at abandoned mine sites in Texas are very high. A summary of published rates in other areas would put these figures in perspective but there are in fact few data concerning rates of incision and sheetflood erosion under conditions of interest here. Of the available data, most are based solely on measurements of suspended load. Yet some studies and personal observations have shown that bedload is a significant component of the total yield of sediment from mined areas. The Federal Interagency River Basin Committee (1953) reported that maximum sediment yield in a small drainage basin in the Loess Hills of Iowa corresponds to a projected erosional rate of 12.8 m/1,000 yr (42 ft/1,000 yr). This is one of the highest rates of sediment loss noted anywhere (Schumm, 1977). Of course, this value is not a reliable indicator of the actual erosion that would take place over 1,000 years. Expression of the rate in this format is for ease of visualization and comparison. A similar extrapolation of the coefficient of regression for all data obtained during the current study (table 8) yields a weighted-mean rate of 26.8 m/1000 yr (87.9 ft/1,000 yr). The arithmetic-mean rate of erosion (table 7) is even higher, 46.3 m/1,000 yr (151.8 ft/1,000 yr), and maximal rates are higher still. These values are much greater numerically than that for the Loess Hills. However, direct comparison of the rates is misleading because of major differences in the size of affected areas and the manner in which erosion was measured. But in a general sense the comparison supports the conclusion that denudation and incision at selected mine sites in Texas is severe.

Interpretation

It may be possible to account for this exceptional erosion by reconsidering the ordination of rates (fig. 36). The rates are plotted with respect to the time (years before present) of abandonment of the mines. When relations among the data were evaluated earlier in this report, chronology seemed to control magnitude. The highest rates are those that were felt in the first four years after abandonment. Long-term rates are substantially lower and approximately equal to the coefficients of regression for individual families of data (table 8; fig. 36). However, rates also appear to vary geographically, from east to west, in that the highest rates (at 4 and 10 yr) were observed at mine sites in East-Central and northeastern Texas. The data are too scanty to confidently distinguish these possible causes of variation statistically. But it is interesting to consider why longitude might be an important factor.

Rainfall probably is the direct cause. Total annual precipitation is much greater in East-Central and northeastern areas where high, initial rates of erosion were observed than in North-Central Texas where long-term rates were measured. These data appear to contradict the conclusions of Langbein and Schumm (1958) who recognized the existence of erosional thresholds linked to precipitation. This concept of an erosional threshold is predicated on the realization that rainfall controls both runoff and vegetation. Where precipitation is greater than 31.6 cm (14 inch), the upper limit of this threshold, the corresponding increase in vegetative cover will retard erosion. Where precipitation is less than about 25.4 cm (10 inch), the lower limit, erosion is inhibited by the small amount of runoff, even through vegetative cover also is minimal. Erosion is maximized between these specified limits but falls off smoothly beyond them. Precipitation exceeds the upper limit in each of the three regions where erosional data were obtained during the current study, and generally increases from west to east (Bowmar, 1983, fig. 28). Thus, erosion should decrease in the same direction, but just the opposite is true. The reason for this discrepancy is that another factor, toxicity of the substrate, had reduced vegetation at the mine sites despite an eastward increase in precipitation. Without a protective cover of plants the substrate is heavily eroded by the increased regional rainfall, much more heavily than at mine sites farther west or at sites other than mines in the same region. Under these circumstances the relation defined by Langbein and Schumm does not adequately express soil loss relative to incident precipitation.

SUMMARY

Environmental conditions at abandoned lignitic and bituminous-coal mines in Texas are complex and locally adverse. Damage in some areas is conspicuous but little known outside the immediate vicinity because most sites are small and isolated. In addition, hazards and reduced productivity in the most severally affected areas have long made these sites unattractive or inaccessible and thereby prevented potentially conflicting land use. With no one to call attention to these conditions they have been the subject of few investigations. No unified description or analysis of the environmental geology of the state's abandoned coal mines has ever been published.

Geological effects vary in type and intensity from site to site: some were direct results of mining whereas others developed or intensified long after the mines were abandoned. Conditions have continued to deteriorate in a number of areas but were emended naturally elsewhere. The current condition of mine sites in the state reflects the original impact of mining, offset or exacerbated by subsequent land use, deliberate mitigation (if any), and natural processes whether destructive or restorative. In some instances the relative contributions of these processes are obscure.

The objectives of the present study were to recognize and assess conditions at these mine sites. Some of the findings are geologically revealing, a few might have historical interest, and many may find practical application in programs to reclaim these and other disturbed areas. Major findings and their possible relevance are summarized below.

The mining of coal in Texas was much more extensive than has generally been supposed, and may have begun much earlier. Mines in South Texas were established at least at the same time as those in eastern areas of the state, by about 1810, and possibly began 60 years before. There are more than 260 abandoned coal mines statewide. Several of these mines have not been reported previously and the total number of mines is much larger than that given in other accounts. The mines are located in all parts of Texas except the Panhandle and sections of the Trans-Pecos and central regions. The large number of sites and their distribution through most areas of the state increases the probability that adverse conditions have developed at some mines. In fact, there are many mines that exhibit a variety of environmental hazards.

Reclamation has reduced the number of seriously affected mine sites. At least 17 such sites have been reclaimed by State and Federal agencies since the introduction of various remedial programs in the mid-1970's (unpublished records, Railroad Commission of Texas and U. S. Soil Conservation Service). An undetermined but small number of mined lands were completely or partly converted to other uses by private concerns before and during this period. A few other sites lie within areas of active mining. The reclamation programs for the new mines will restore the older sites as well, or the older mines will be preserved for their historic interest but isolated to prevent environmental damage to adjacent areas.

Most abandoned mines in Texas are unreclaimed. Natural restorative processes have reduced or eliminated hazards in a number of areas. However, significant problems persist and may be worsening at the remaining sites. Open shafts, drifts, and steep-walled pits are found at several mines, and some of these have been used as incidental landfills. A few sites retain deteriorating structures and equipment but most do not appear to threaten succeeding land uses. Subsidence and perhaps underground fires may be continuing in two or three isolated areas. Effects there are minor although these conditions could develop at other mine sites in the state and thus are cause for prudent concern.

Because they were significant effects in the past and could again represent a serious hazard, at least locally, subsidence and underground fires were discussed at considerable length in this report. I proposed a simplified model for predicting ultimate subsidence. This model was not tested in detail here because of insufficient data regarding otherwise suitable underground mines. I also developed a method for estimating the maximum temperature attained during an underground fire. The method is based on the systematic description of samples in terms of their relative vitrification. Stages of vitrification recognized in hand samples and under the scanning-electron microscope were calibrated using data from ceramics tests performed on spoil. Alternatively, fusion temperatures of fly ash may provide an acceptable indication of the thermal behavior of spoil materials. Either method can be used to infer past thermal conditions at mine sites. The technique may prove beneficial in reclamation programs because it can be used to define the lateral extent and intensity of combustion within spoil or seams of coal.

The principle causes of environmental degradation at most mine sites in Texas are erosion and the formation and release of toxic leachates. There are too few data concerning the geochemistry of abandoned mines to fully characterize individual sites. However, potentially hazardous concentrations of sulfuric acid and trace metals have been observed at those few locations at which tests have been performed. And qualitative observations clearly indicate that toxic conditions may exist in many areas. Known effects of leachates at the state's coal mines are limited to devegetation of spoil mounds and adjacent areas and local effects on streams. In addition, there have been instances of molybdenum toxification of livestock at reclaimed uranium mines in South Texas. Molybdenum is released from absorption and other types of fixation by an increase in pH. Reclamation generally necessitates neutralization of sulfuric acid formed by the oxidation of sulfide minerals within spoil. The potential release of molybdenum from emended spoil should be evaluated in every reclamation program. Analyses of total concentrations and the geochemical distribution of toxic metals would be invaluable in planning such programs and could prove cost effective. By adequately characterizing the spoil to be used in filling and regrading a mine site, materials with undesirable properties could be deeply buried, emended, or avoided altogether. This information could result in cost savings in terms of earth moving, spoil treatment, and eventual suitability of the site for reuse.

The petrology of sulfide minerals in spoil and coal is another important source of information concerning toxic leachate. The formation of sulfuric acid depends on the rate of sulfide oxidation. Therefore the relative reactivities and concentrations of various minerals become important. Marcasite generally is a more unstable sulfide under oxidizing conditions than is pyrite. Framboidal pyrite is more reactive than euhedral pyrite. However, euhedral crystals of pyrite in the textural range of framboids and polyframboids were discovered in weathered coal during the present study. The site at which these samples were collected is severely devegetated, almost certainly because of strongly acidic conditions within the spoil. Microcrystalline euhedra of pyrite are by far the most abundant sulfides in the samples. They probably enter into oxidizing reactions more readily than has been supposed because of their large surface areas relative to mass.

Rates of erosion at abandoned coal mines in the state are extremely high. Devegetation owing to phytotoxic conditions permits unretarded sheetflooding and incision such that these rates are among the highest ever reported. Sediment removed from these sites has accumulated on slopes and in streams and reservoirs below the state's mine sites. This sediment altered local patterns of runoff and reduced the storage capacity of reservoirs. Floods have breached the dams at two of these small lakes at least in part because of reductions in capacity.

Although most of the abandoned mine sites are small and effects are localized environmental impact in a few areas is severe. Some sites will be reclaimed through existing public and private efforts but others may remain unrestored for many years. Additional studies are needed to adequately characterize conditions at the most severely affected sites. These studies should include an extensive, well-designed program of geochemical analyses, geohydrologic investigations, and petrologic descriptions of spoil. To the extent possible these studies should be tightly coordinated.

APPENDIX A: DESCRIPTION OF CLINKER ("SLAGITE") FROM SPOIL MOUNDS AT COAL MINES IN TEXAS

(Ba1H) Bastrop Co., mine site Ba/Ba-4-1: subrounded to subangular blocky clasts of shale (no sedimentary structures evident), and slightly to moderately vesicular glass. Clasts poorly sorted, 0.1 to 3.0 cm maximum dimension, 20% of sample. Glass surrounds clasts, 80% of sample. Smaller vesicles in glass spheroidal, mostly 0.1 cm in diameter, largest vesicles (few) oblate spheroidal, maximum 4.0 cm in diameter. Luster of glass dull resinous to vitreous, some areas faintly metallic. Color of shale: (dry) very pale orange (10 YR 8/2) and grayish orange (10 YR 7/4); (wet) colors essentially unchanged. Color of glass: (dry) dusky blue (5 PB 3/2) and dusky red (10 R 2/2). Size of sample 9.0 x 7.0 x 5.0 cm. Clasts mostly dense and procellaneous, some microporous and chalky; all are structureless, presumably because of fusion. Surface of glass marked by very few vesicles. Neither closed, discrete prominences nor open-chambered vesicles more than scarcely evident. However, broken surfaces reveal abundant vesicles within glass. Fact that so few bubbles raised or broke surface of melt liquid may indicate viscosity of liquid was higher than that of other liquids producing vesicular glass in samples described here.

(Ea1H) Eastland Co., mine site Ea/B1-1-1: subangular blocky and platy clasts of horizontally laminated shale, and moderately vesicular glass. Bimodal distribution of clast sizes: (a) 5.0 to 8.5 cm maximum dimension, 60% of sample; (b) less than 1.0 cm maximum dimension, 30% of sample. Glass mostly between clasts, composing 10% of sample. Vesicles in glass spheroidal, mostly 0.1 cm in diameter, but few vesicles as much as 0.6 cm in diameter. Luster of glass (dry) mostly resinous, some areas vitreous. Color of shale: (dry) dominantly pale reddish brown (10 R 5/4) and brownish gray (5 YR 4/1); (wet) dark reddish brown (10 R 3/4) and blackish red (5 R 2/2). Color of glass: (dry) medium dark gray (N4) to dark gray (N3); (wet) brownish black (5 YR 2/1). Size of sample 14 x 7 x 7 cm. Entire mass solidly bound (fused) together but most clasts still become moderately plastic when fully hydrated, indicating only partial fusion. One clast almost entirely viscous. Platy clasts tough (even when hydrated) and undistorted, indicating complete vitrification; composition of platy clasts (few present) apparently differs from that of blocky clasts. Blocky clasts distorted by heat and compaction, and exhibit incipient fusion to near vitrification along common surfaces (interior of mass). Open fractures cutting across laminae within these clasts probably caused by rapid dessication prior to fusion. Darkened interiors of some clasts also indicate rapid heating (see Potter and McKnight, 1931, p. 60, 61).

(Ea2H) Eastland Co., mine site Ea/B1-1-1: subangular to subrounded blocky clasts of horizontally laminated shale, and moderately vesicular glass. Clasts 7.0 to 8.5 cm maximum dimension, 80% of sample. Glass within, between, and upon clasts, binding entire mass together and composing 20% of sample. Vesicles in glass mostly 0.1 to 1.0 cm, smaller vesicles spheroidal, larger vesicles spheroidal to oblate spheroidal. Interior of one large, subrounded clast (exposed along break) exhibits incipient fusion and is very finely vesicular, pores mostly 0.01 cm in diameter, 0.6 cm in maximum diameter. Luster of glass (dry) mostly resinous to slightly vitreous. Color of shale: (dry) light brown (5 YR 6/4) and moderate reddish orange (10 R 6/6); (wet) moderate reddish brown 10 R 4/6 and light brown (5 YR 5/6). Color of glass: (dry) dusky blue (5 PB 3/2): (wet) grayish black (N2). Size of sample 10 x 8 x 6.5 cm. Laminae of one subangular blocky clast have separated (by as much as 0.2 cm) and been distorted by interlaminar, incipient fusion, with moderately vesicular glass exposed between some laminae. Exterior of this clast exhibits moderate distortion due to compaction and apparent abrasion against contiguous clasts while still plastic.

(Ea3H) Eastland Co., mine site Ea/B1-1-1: subangular (few subrounded) blocky to platy clasts of horizontally laminated shale, and slightly to moderately vesicular glass. Bimodal distribution of clast sizes: (a) 4.5 to 5.0 cm maximum dimension, 30% of sample; (b) less than 1.0 cm (few to 2.0 cm) maximum dimension, 40% of sample. Glass between clasts and forming underside of mass (direction of flow of melt liquid preserved in glass, indicating orientation of sample at time of fusion). Glass binds entire mass together and composes at least 30% of sample. Vesicles in glass spheroidal to irregularly shaped (due to subsequent deformation of clasts), mostly 0.01 to 0.1 cm in diameter, but few vesicles as much as 1.0 cm in diameter. Luster of glass mostly resinous, some areas metallic (finely specular) to greasy. Color of shale: (dry) moderate red (5 R 5/4); (wet) dark reddish brown (10 R 3/4). Color of glass: (dry) mostly dark gray (N3) to medium dark gray (N4), that with metallic luster is dusky red (5 R 3/4); (wet) grayish black (N2) to greenish black (5 G 2/1). Size of sample 7.5 x 6.5 x 3.5 cm. Some laminae of one subangular blocky clast have separated slightly due to interlaminar, incipient fusion. On upper surface of sample, fusion is merely incipient while lower surface is entirely viscous. This is an indication of the poor thermal conductivity of the shale and interstitial glass.

(Ea4H) Eastland Co., mine site Ea/Cn-2-3: single subangular platy clast of horizontally laminated shale, and moderately to highly vesicular glass. Clast 9.0 cm maximum dimension, 50% of sample. Glass within and upon clast, composing 50% of sample. Vesicles in glass spheroidal to oblate spheroidal, 0.1 to 2.0 cm in diameter where glass covers exterior of clast (vesicles continuously linked across surface). Vesicles within clast spheroidal, 0.01 to 0.1 cm in diameter. Luster of glass (dry)mostly resinous, some areas vitreous, small area metallic. Color of shale: (dry) moderate red (5 R 4/6); (wet) dark reddish brown (10 R 3/4). Color of glass: (dry) mostly dusky blue (5 PB 3/2), small areas dark greenish yellow (10 Y 6/6) and, where luster is metallic, dusky red (5 R 3/4); (wet) mostly grayish black (N2), color of other areas essentially unchanged. Size of sample 9.0 x 6.5 x 5.0 cm. Grade of pyrogenesis varies markedly across clast, from interlaminar, incipient fusion to vitrification (partly obscuring original lamination) to viscous fusion (affecting both the interior and exterior of clast). Gradation reflects at least local thermal gradient in spoil mound at time of fusion. Even more locally, laminae separated and were folded around region of viscous fusion within interior of clast where carbonaceous material may have been concentrated (see Potter and McKnight, 1931, p. 60, 61).

(PP1H) Palo Pinto Co., mine site PP/G-2-9: Blocky mass of highly vesicular glass (holohyaline material). Vesicles in glass spheroidal, mostly 0.1 cm in diameter. Luster of glass vitreous. Color of glass: (dry) brownish black (5 YR 2/1); (wet) grayish black (N2). Size of sample 3.0 x 2.5 x 2.0 cm. Material completely vitreous and extremely porous; pores apparently interconnected, as sample also extremely permeable. Entire surface of sample consists of small, open pores. Gas-filled bubbles in melt liquid probably collected as buoyant froth beneath film of moderately viscous melt liquid. As number of bubbles increased, blister was raised on film. Most large masses of vesicular glass (themselves vesicles in an extended sense) in clinker may have formed in this way, enclosing many smaller, discrete vesicles. Sample likely formed interior of sphere of this kind from which shell-like coating was broken. Largest sample of open-chambered glass seen at any mine in state. Sample apparently reached temperature of viscous fusion.

(Y1H) Young Co., mine site Y/N-2-7: rounded platy clasts of horizontally laminated shale, and moderately to highly vesicular glass. Clasts 3.0 to 8.5 cm maximum dimension, 30% of sample. Glass surrounds clasts, composes 70% of sample. Vesicles in glass spheroidal, mostly 0.1 to 1.5 cm in diameter, few to 4.0 cm. Luster of glass mostly resinous, some areas vitreous; interior surface of broken vesicles vitreous. Color of shale: (dry) mostly pale reddish brown (10 R 5/4), some moderate reddish orange (10 R 6/6); (wet) mostly moderate reddish brown (10 R 4/6), some pale reddish brown (10 R 5/4). Color of glass: (dry) medium bluish gray (5 B 5/1) to medium dark gray (N3); (wet) dark gray (N3), interior of large vesicles dark reddish brown (10 R 3/4). Size of sample 10.0 x 9.0 x 6.0 cm. Lamination of clasts virtually obscured by incipient fusion and formation of vesicles. Glass clearly preserves flowage patterns of melt liquid. Most of sample reached temperature of viscous fusion.

(Y2H) Young Co., mine site Y/N-2-7: subrounded to subangular blocky clasts of horizontally laminated shale, and moderately to highly vesicular glass. Clasts poorly sorted, mode approximately 3.0 cm maximum dimension, largest 8.0 cm, smallest mostly 1.0 to 2.0 cm; 60% of sample. Glass between and within clasts and forming most of underside of sample. Glass binds entire mass together and composes 40% of sample, but mass remains porous throughout. Vesicles in glass spheroidal to irregularly shaped (due to subsequent distortion of clasts), mostly 0.1 to 0.4 cm in diameter, some possibly as much as 2.0 cm. Luster of glass resinous. Color of shale (discrete clasts): (dry) mostly moderate reddish brown (10 R 4/6), some light brown (5 YR 5/6), pale yellowish orange (10 YR 8/6), and dark yellowish orange (10 YR 6/6); (wet) mostly moderate reddish brown (10 R 4/6), some dark yellow orange (10 YR 6/6) and moderate orange pink (5 YR 8/4). Color of glass: (dry) grayish black (N2) to medium dark gray (N4); (wet) grayish black (N2) to greenish black (5 G 2/1). Surface of many clasts partly covered with thick efflorescence of mineral (color: very light gray, N8) that is not soluble in dilute (10%) hydrochloric acid. Size of sample 14.0 x 10.0 x 7.0 cm. Horizontal laminations still recognizable in some clasts but obscured in many others. Incipient fusion affects some clasts, making them structureless. Other clasts internally distorted by compaction while plastic; margins of many contiguous clasts interpenetrating, clearly indicating plastic deformation of the mass as a whole. Preferred orientation of pores in some otherwise structureless clasts is indicator of relictual lamination. Loss of identifiable sedimentary structures within clasts is progressive: (1) formation of small amount of glass along laminations; (2) evolution of tiny pores along laminations; (3) in some clasts, separation of laminae and formation of more glass; (4) in other clasts, compaction and fusion of laminae; (5) plastic deformation of clasts by folding, interpenetration, and distortion of originally spheroidal pores; and (6) compaction of entire mass, reducing interparticle space between clasts, squeezing bubble-filled melt liquid (vesicular proto-glass) into remaining cavities. (Note: squeezing, which produces movement along path of least resistance regardless of orientation of mass, generally distinguishable from flowage due to gravity. Recognizable flowage is across single confining surface. Squeezing or compression is between two or more confining surfaces evidently brought toward one another.

<u>(Y3H)</u> <u>Young</u> <u>Co.,</u> <u>mine</u> <u>site</u> <u>Y/N-2-7</u>: single subrounded blocky clast of horizontally laminated shale, and moderately vesicular glass. Clast 6 cm maximum dimension, 70% of sample. Glass within and upon clast, composing 30% of sample. Vesicles in glass spherical to oblate spheroidal, in three discrete classes of size: (a) 0.01 cm (interstitial pores within shale laminae); (b) 0.1 to 0.3 cm (interlaminar pores in glass); (c) 0.5 to 1.0 cm (in glass

on surface of clast). Luster of glass mostly resinous, some areas metallic. Color of shale: (dry) polar variation within clast, from moderate reddish brown (10 R 4/6) to moderate yellow (5 Y 7/6); (wet) moderate reddish brown (10 R 4/6) to dark yellowish orange (10 YR 6/6). Zone of transition covered with glass. Much more glass present at red end of clast, which presumably was hotter or was heated more rapidly. Color of glass (including area with metallic luster): (dry) olive black (5 Y 2/1); (wet) very dusky red (10 R 2/2). Size of sample 6.0 x 5.0 x 3.5 cm. Laminae of red end of clast separated, ruptured (perpendicular to lamination), and deformed by interlaminar, incipient fusion. Laminae of yellow end of clast all but completely obscured by fusion and evolution of abundant, tiny, interstitial vesicles. This pattern indicates red end of clast was exposed to higher temperatures more quickly, and in oxygenated microenvironment, than was yellow end which apparently occupied zone of oxygen-depletion, and was slightly farther from local concentration of heat.

APPENDIX B: ABBREVIATIONS USED IN NUMBERING MINE SITES

County (Code)

Anderson (A)
Bastrop (Ba)
Bexar (Bx)
Bowie (Bo)
Brewster (Br)
Coleman (C)
Eastland (Ea)
Erath (Er)
Fayette (F)
Harrison (H)
Henderson (Hn)
Hopkins (Hp)
Houston (Ho)
Hudspeth (Hu)
Jack (J)
Lee (Le)
Leon (L)
Maverick (Mv)
McCulloch (Mc)
Medina (Me)
Milam (Mi)
Montague (M)
Nacogdoches (N)
Palo Pinto (PP)
Parker (P)
Presidio (Pr)
Rains (R)
Robertson (Ro)
Shelby (Sh)
Stephens (S)
Titus (T)
Upshur (U)
Van Zandt (V)
Webb (We)
Wise (W)
Wood (Wd)
Young (Y)

Total: 37

Topographic Map (Code): County (in which mine is located)

* Map at a scale of 1:62,500 (15-min series)

Alba (A): Rains, Wood

Alcoa Lake (AL): Milam

Antelope (An): Jack

Athens (At)*: Henderson

Bastrop (Ba)*: Bastrop

Bernie Lake (BL): Eastland

Breckenridge (B): Stephens

Bridgeport East (BE): Wise

Bridgeport West (BW): Wise

Brushy Mound (BM): Montague

Calvary (Ca): Wood

Calvert (Cv): Robertson

Center (Ce)*: Shelby

Cisco North (CN): Eastland

Como (Cm): Hopkins

Cookville (Ck): Titus

Corley (Co): Bowie

Crystal Falls (CF): Stephens

Darco (D)*: Harrison

Deadmans Hill (DH): Maverick

Dolores Ranch (DR): Webb

Eagle Mountains Northeast (EM): Hudspeth

Edgewood (Ed): Van Zandt

Elkhart (El)*: Anderson

Fife (FF): Coleman, McCulloch

Gettysberg Peak (GP): Presidio

Gordon (G)*: Erath, Palo Pinto

Hammond (H): Robertson

Hen Egg Mountain (HE): Brewster

Hicks (Hi): Lee

Lake Eddleman (LE): Young

Ledbetter (Ld): Fayette

Lexington (Lx)*: Bastrop

Lovelady North (LN): Houston

Lynn Creek (LC): Jack

Lytle (Ly): Medina

Malakoff (Mk): Henderson

Markley (M): Young

Maysfield (My): Robertson

Mineral Wells (MW)*: Parker

Newcastle (N): Young

Newsome (Nw): Wood

Palafox (Pa)*: Webb

Postoak (Po): Jack

Proffitt (P): Young

Quemado Southeast (QSe): Maverick

Reddy Mountain (RM): Erath

Rockdale East (RE): Milam

Rockdale West (RW): Milam

Round Prairie (RP): Leon

Selma (Sl): Montague

Smithville (Sv)*: Bastrop

Somerset (S): Bexar

Sulphur Springs Southeast (SSe): Hopkins

Thomas (To): Upshur

Thrifty (Th): Coleman

Timpson (Ti)*: Nacogdoches, Shelby

Winfield (W): Titus

Yantis (Y): Hopkins

TOTAL: 59

NOTE: Codes assigned to three of the topographic maps above differ from codes originally used by Newsome and Smith (Railroad Commission of Texas, Surface-Mining and Reclamation Division, Austin): Athens (was "A", changed to "At"); Center (was "Cn", changed to "Ce"); and Thomas (was "Th", changed to "To").

APPENDIX C: SUMMARY OF ENVIRONMENTAL GEOLOGIC CONDITIONS AT ABANDONED COAL-MINES IN TEXAS

Alphanumeric identifier: uniquely identifies each mine site. Consists of four parts arranged in the following manner,

(a)/(b) - (c) - (d),

where (a) is a code of one or two letters identifying the county in which a particular mine site is located (appendix B); (b) is a code of one to three letters identifying the topographic map covering the site (appendix B); (c) is a numeral of one digit identifying the map quadrant covering the site (numbered 1 through 4 clockwise from the southeastern quadrant of the map); and (d) is a numeral of one or two digits uniquely identifying the site among all sites covered by that map (numbers assigned sequentially).

Name: historic name (if any) by which mine was known.

Area: areal extent of mine site, expressed in hectares (ha) or units of 10,000 m^2. The factor for converting measurements to English units (acres) is 1.0 ha = 2.471 ac.

<u>Type of Mine</u>: U - underground: (1) drift; (2) slope; (3) shaft. S - surface: (1) area; (2) contour; (3) cut or pit (small mines only).

<u>Open entryways/air shafts</u>: the number of opening that still afford access to the interior of an underground mine.

<u>Debris</u>: (1) structural; (2) mechanical; (3) both.

<u>Spoil</u>: size of the mound or sheet of spoil at a site (if any; combined area if more than one): (1) > 1,000 m^3; (2) 1,000 m^3 > size > 100 m^3; (3) < 100 m^3.

<u>Combustion</u>: (x) combustion at site (in the past); (blank) no evidence of combustion found.

<u>Leachate</u>: geochemical leachate appears to affect: (1) soil; (2) surface water; (3) ground water; (4) combination.

<u>Erosion</u>: (1) sheet/rill; (2) gully/stream; (3) both.

<u>Deposition</u>: (1) slope; (2) stream; (3) impoundment; (4) combination.

<u>Runoff</u>: (1) increase; (2) decrease; (3) diversion.

<u>Recharge</u>: (1) increase; (2) decrease.

<u>Subsidence</u>: (a) pit; (b) basin; (c) both; letter preceded by number of features (unless 1).

<u>Other/comment</u>: additional remarks.

Other Symbols

N = negligible

? = unknown or uncertain (= uncertain when used with another symbol)

X = effect noted but not otherwise qualified

(blank) = no effect or "not applicable"

This summary is drawn principally from three sources of information: original observations during this study; Finley and others (1979); and unpublished records of the Railroad Commission of Texas, Surface Mining and Reclamation Division (including personal communication with members of the staff). Additional information was drawn from published references and personal communication with residents of the areas of mining.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
A/El-3-1		<1	U 3	?	?	3	?	?	?	?	?	?	?	Unpublished records, RRCT.
Ba/Ba-4-1		<1	U 3											Same
Ba/Ba-4-2		<1	U 3											Same
Ba/Ba-4-3	Phelan	~1.5	U 3	0	3	2	x	1	3	1	1	N	0	Few trees on soil.
Ba/Ba-4-4		<1	U 3											Unpublished records, RRCT.
Ba/Ba-4-5		~1	U 3	?	?	2	?	?	?	?	?	?	?	At least two former shafts.
Ba/Ba-4-6		<1	U 3	?	?	2	?	?	?	?	?	?	?	Unpublished records, RRCT.
Ba/Ba-4-7		No DATA	-	-	-	-	-	?	-	-	-	-	-	Same
Ba/Ba-4-8		NO DATA	-	-	-	-	-	?	-	-	-	-	-	Same

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Ba/Ba-4-9	Phelan	~1.5	U 3	0	2	2	x	1	3	1	1	N	0	Site of erosion monitoring, this study.
Ba/Ba-4-10	Dunston	3	U 3	2	3	2	x	1	3	4	1	N	a	Complex of structures and mine shafts.
Ba/Lx-2-1		NO DATA	-	-	-	-	-	?	-	-	-	-	-	Unpublished records, RRCT.
Ba/Sv-3-1		NO DATA	-	-	-	-	-	?	-	-	-	-	-	Same
Ba/Sv-3-2		NO DATA	-	-	-	-	-	?	-	-	-	-	-	Same
Ba/Sv-3-3		< 1	U 3	?	?	3	?	?	1	?	?	?	?	Same and aerial photographs.
Ba/Sv-3-4		NO DATA	-	-	-	-	-	?	-	-	-	-	-	Unpublished records, RRCT.
Ba/Sv-3-5		< 1	U 3	?	?	3	?	?	1	?	?	?	?	Same and aerial photographs.
Ba/Sv-3-6		< 1	U 3	?	?	3	?	?	3	?	?	?	?	Same

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Ba/Sv-3-7		< 1	U 3	?	?	3	?	?	3	?	?	?	?	Same
Ba/Sv-3-8		< 1	U 3	?	?	3	?	?	3	?	?	?	?	Same
Ba/Sv-3-9		< 1	U 3	?	?	3	?	?	3	?	?	?	?	Unpublished records, RRCT.
Ba/Sv-3-10		NO DATA	-	-	-	-	-	?	-	-	-	-	-	Same
Bx/S-3-3	Bracken-ridge Coal Co.	~ 1.5	U 3	2	2	3							b	Same and aerial photographs
Bx/S-3-4	Same	< 1	U 3	0	1	3							0	Same
Bx/S-3-5	Same	~ 2	U 3	1	2	3							b	Same
Bx/S-4-1	Kirkwood?	2	U 3	0	2	3							b	Same
Bx/S-4-2	Same?	2	U 3	0	2	3							b	Same

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Bo/Co-3-1	Carbon-dale Coal Co. ?	?	U 3	?	?	?	?	?	?	?	?	?	?	Unpublished records, RRCT.
Br/HE-4-1		~5	U 3	7	3	2			3		1			Same
Br/HE-2-2	Chisos Mining Co.	~5	U3 S1	1	3	1			3		1			Periodically mined to produce soil conditioner.
C/FF-4-14	Star and Crescent	6	U 2	3	3	1	x	4	3	4	1	1	6 C	Three mines at this site.
C/FF-4-15	Gibson	4	U 3	1		2		1	3	4	1	N	a	Shaft reopened for prospecting, 1975.
C/Th-3-5	Silver Moon	<1	U 3			2		1	1					Two shafts; site of active clay pit
Ea/BL-1-1		2	U 3		1	2	x	1					3 C	Recent subsidence (1979). Extensive combustion.
Ea/BL-4-2		<1	U 3	1		3		1						Open shaft 10m deep.
Ea/BL-1-3		~1.5	U 3	1		3							a	

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Ea/CN-2-2		<1	U 3											
Ea/CN-2-3		2	S 2			1	x	4	3	3	1			Caused failure of impoundment; in-flowing leachate.
Ea/CN-2-4		<1	U 2						1		1			
Ea/CN-2-5		<1	U 3?			3		4	2	3	1		3 a	Sedimentation within impoundment.
Er/G-2-55	No.3	2	U 3			1	x	4	3	2	1	1		Severe sedimentation along stream.
Er/G-2-56	New No. 3	1	U 3		3	1	x	1	3	1	1	1		Steep-sided spoil mound; large area of devegetation.
Er/G-2-57	No. 2	1.5	U 3			1	?	1	1	1	1	1		
Er/G-2-58	No. 4	1.5	U 3			2	?	1		1				
Er/G-2-59	No.1	3.5	U 3			1	?			1		1		

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Er/G-2-60		1.5	U 3			1	?	1	1	1	1	1		
Er/G-2-61	No. 6	1.5	U 3		3	1	?	2	3	3	1	1		Sedimentation within impoundment.
Er/G-2-62	No. 5	1.5	U 3			1	?	1	3	1	1	1		
Er/G-2-63	No. 9	4	U 3			1	x	1	3	1	1	1	b	Extensive spoil mound; devegetation, combustion.
Er/RM-3-11	No. 12	3.5	U 3			1	?	1	3	1	1	1		
Er/RM-3-12	New No. 1	2.5	U 3			1	?	1	1	1	1	1		
Er/RM-4-13	Newcastle	1	U 3			1	?	1	1	1	1	1		
F/Ld-1-1		1	U 3			2	?	?					b	Unpublished records, RRCT.
H/D-3-1	Darco	25	S 1		2	1	x	1	3	4	1	1		Extensive spoil mounds.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Hn/At-3-1		2	U 3			2	?	?	1	1			?	Unpublished records, RRCT.
Hn/At-3-2		2	U 3			2	?	?	1	1			?	Same
Hn/At-3-3		2	U 3			2	?	?	1	1			?	Same
Hn/Mk-4-1		<25	S 2		2	1		4	3	4	1	1		Extensive spoil mounds.
Hp/Cm-3-1		2	U 3			1	?	1	1	1	1	?	?	Unpublished records, RRCT.
Hp/Cm-2-2 through Hp/Cm-2-12		2	U 3			1	?	1	1	1	1	1	b	Same. All sites similar.
Hp/SSe-4-1		?	U 3	-	-	-	-	?	-	-	-	-	-	Unpublished records, RRCT.
Hp/SSe-1-2	Wallace	6	S 1		2	1		4	3	4	3	2		Site reclaimed (1980).
Hp/Y-3-1	Lumsden	4	S 1			1		4	3	4	3			Site reclaimed (1980).

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Ho/LN-2-1 through Ho/LN-2-7		2	U 3			2	?	1	3	1	1	N	b	Unpublished records, RRCT. Sites similar.
Hu/EM-4-1		1	U 1			2	?	?	3	1	1		b	Unpublished records, RRCT; aerial photographs.
Hu/EM-4-2		2	U 3		2	2	?	?	3	4	1		?	Same
Hu/EM-1-3		<1	U 3			2	?	?	3	1	1		?	Same
Hu/EM-3-4	Eagle Spring	3	U 3		2	1	?	?	3	1	1		a	Same
Hu/EM-3-5		1	U 3			2	?	?	3	1	1		?	Same
Hu/EM-4-6		2	U 3			2	?	?	3	1	1		?	Unpublished records, RRCT; aerial photographs.
Hu/EM-4-7		3	U 3		2	1	?	?	3	1	1		b	Same
J/An-1-1		1.5	S 2			3		1	1					

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
J/An-1-3		1.5	S 2			3		1	3	1	3	1		
J/An-1-4		1.5	S 2			3		1	1	1				Aerial photographs.
J/An-1-6		1.5	S 2			3		1	1	1				Same
J/LC-3-10	Jackson	1.5	U 1			3		1	1	1				
J/LC-4-21		1.5	U 1			2		4	2	3	1			
J/LC-4-39		1	U 1			3		1	1	1				Aerial photographs.
J/LC-4-41	Brannon	1	U 2		1	1		4	3	4	3		b	Severe gullying.
J/PO-2-10		1.5	S 2			2		1	3	1	1			Aerial photographs.
J/PO-2-11		1.5	S 2			1		1	1	1	1			Same

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
J/PO-2-13		< 1	U 1			1		1	1	1	1			Aerial photographs.
Le/Hi-2-1 Le/Hi-2-4	through	5	U 3	1	3	3	x	1	3	1	1		2 b	Sites nearby, discussion combined.
L/RP-4-1	Bear Grass	2?	U 3	-	-	-	-	?	-	-	-	-	-	Unpublished rec-cords, RRCT.
L/RP-4-2	Same	2?	U 3	-	-	-	-	?	-	-	-	-	-	Same
Mv/DH-2-1	Lamar	1	U 3			2		1	3	1	1			
Mv/DH-2-2	Olmos	22	U 3	1	2	1	x	4	3	4	1	2	b	Severely disturbed site.
Mv/DH-2-3	International	2	U 3		1	1	x	1	3	1	1		a	Severely disturbed site.
Mv/QSe-1-1	Hartz	4	U 3		2	1	x	4	3	1	1		b	
Mc/FF-3-1		<1	U 3			3		4	1				a	Shaft filled with domestic refuse.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Mc/FF-3-2	Williams	<1	U 3			3		1	3	4	1		a	
Mc/FF-4-3	Finks 1	<1	U 3	1	1			3	1			1		Shaft filled with domestic refuse.
Mc/FF-4-4	Finks 2	1.5	U 3	1	1	2		4	3	1	1		a	
Mc/FF-4-5	Chaffin	1	U 3	2	1	2	x	4	3	1	2	1	a b	Large subsidence basin.
Mc/FF-4-6	Chaffin (part?)	1	U 3	1	1	2		1	3	1	N	1	a b	Shaft reexcavated (since 1975).
Me/Ly-3-1	Carr	15	U 3		3	1	x	4	3	4	1		b	Aerial photographs. Reclaimed (1980).
Me/Ly-3-2	Riley	20	U 3		3	1	x	4	3	4	1		b	Same
Me/Ly-3-3	Riley (part?)	3	U 3			2		1	3	1				Same
Me/Ly-3-4	Bertelli?	3	U 3			2		1	1	1				Aerial photographs.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Mi/AL-3-1	Sandow	930	S 1		2	1	x	4	3	4	1	1		Extensive spoil mounds.
Mi/RE-4-1 Mi/RE-2-15	through	~30	U 3	?	3	1	x	4	3	4	1	1	a	Sites similar.
Mi/RW-2-1		?	?	-	-	-	-	?	-	-	-	-	-	Unpublished re-cords, RRCT.
M/BM-4-1	Stephens (part)	<1	U 3	1	3	1	x	4	3	4	1	1	a	Unstable, water-filled shaft.
M/BM-1-3	Same	<1	U 3	1	1	3		4	1	1		2		Stock water with-drawn from shaft.
M/BM-1-4	Same	16	U 2	1	3	1	x	4	3	4	1		a	Historic Engi-neering site.
M/BM-3-5	Bowie	2	U 3		1	2	x	4	1	4	1	1	b	
M/Sl-4-1		<1	U 1			2		1	1	1	1		a	Site of earth slide
N/Ti-2-3		3	U 3	-	-	-	-	?	-	-	-	-	-	Unpublished re-cords, RRCT.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
PP/G-2-1	Obel	1	U 3	1		1	x	1	3	1	1			
PP/G-1-2 PP/G-1-6,	through PP/G-1-8	5	U 2		2	1	x	1	3	1	2			Sites similar, discussed together.
PP/G-2-7	Mt. Marion	4	U 3		2	1	x	1	3	4	1		a	
PP/G-2-9	Lyra Siding	3	U 3		3	1	x	1	3	1	2	1	b	Extensive combustion.
PP/G-2-10, and	PP/G-2-11, PP/G-2-12	9	U 3		2	1	x	1	3	1	2	1	a	Sites similar, discussed together.
PP/G-1-51 PP/G-1-54	through	17	U 3			1	x	1	3	1	2		a	Same
P/MW-1-3 P/MW-1-4	and	4	U 3		2	2	?	1	2	4	3		b	Aerial photographs.
P/MW-1-5 P/MW-1-10	through	2	U		2	2	?	1	1	1	1			Same
P/MW-1-13 P/MW-1-14	and	1	U 2		2	1	?	1	1	1	1			Same

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Pr/GP-3-1	San Carlos	5	U 1	1	2	2	?	4	3	4	1			Unpublished records, RRCT.
Pr/GP-3-2 Pr/GP-2-4	through	1	U 3			2	?	1	1	1	1			Same. Sites similar.
R/A-3-6		?	?	-	-	-	?	-	-	-	-	-	-	Unpublished records, RRCT.
Ro/Cv-3-1		3	U 3			2	?	1	1	1	2	1	b	Aerial photographs.
Ro/Cv-3-2		2	U 3			2	?	1	1	1	2	1	b	Same
Ro/H-2-1		2	U 3			2	?	1	1	1	1	1		Same
Ro/My-4-1		2	U 3			2	?	1	1	1	1	1		Same
Sh/Ce-2-1		?	?	-	-	-	-	?	-	-	-	-	-	Unpublished records, RRCT.
Sh/Ce-2-2		?	?	-	-	-	-	?	-	-	-	-	-	Same

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Sh/Ti-3-1	Hammer	4	U 3			1	x	1	3	4	1		b	Extensive subsidence.
Sh/Ti-2-2		2	U 3	?	?	2	?	?	?	?	?	?	?	Unpublished records, RRCT.
S/B-2-1		5.5	S 2			2		2	3	3	1			
S/CF-1-1	Berry Meadows	<1	U 1	1		3				1	N			Mine roof removed.
S/CF-1-2	Jake Wizeart	1.5	U 1			3		1	1				b	
S/CF-1-3		<1	U 1	1	1									Open drift.
S/CF-1-4		<1	U 1			3		1	1	1				
S/CF-1-5		<1	U 2			3		1	1	1				
T/Ck-2-1		?	U 3	-	-	-	-	?	-	-	-	-	-	Unpublished records, RRCT.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
T/W-2-1		?	U 3	-	-	-	-	?	-	-	-	-	-	Unpublished re- cords, RRCT.
T/W-2-2		?	?	-	-	-	-	?	-	-	-	-	-	Same
U/To-1-1		NO DATA	?	-	-	-	-	?	-	-	-	-	-	Unpublished re- cords, RRCT.
U/To-1-2		NO DATA	?	-	-	-	-	?	-	-	-	-	-	Same
V/Ed-4-1		NO DATA	?	-	-	-	-	?	-	-	-	-	-	Same. Site inundated by lake.
V/Ed-1-2		NO DATA	?	-	-	-	-	?	-	-	-	-	-	Unpublished re- cords, RRCT.
We/DR-3-1	Santo Tomas	4	U 3		3	1	x	4	3	4	1	1		Large spoil mound.
We/DR-3-2	Darwin	3	U 3		3	1	x	4	3	4	1	1	b	
We/DR-3-3	Hunt	2	U 1		3	1	?	1	3	4	1	1	b	

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
We/DR-3-4	San Jose	3	U 3		3	1	?	1	3	1	1	1		
We/DR-3-5	Dolores	3	U 3		3	1	x	1	3	1	1	1	b	Mining may have begun in 1750's.
We/Pa-1-1		2	U 3		?	2	?	1	3	1	1			Unpublished records, RRCT.
W/BE-3-2		<1	U 2			2	x	1	1	1	1		b	
W/BE-3-4 W/BE-3-6	through	5	U 2			2	x	1	1	1	1		a	Sites similar, combined for
W/BE-3-9 W/BE-3-14	and through													discussion. Some sites
W/BE-3-16 W/BW-4-1	and													effectively reclaimed.
W/BW-4-3	Grill	1	U 2			2		4	1	3		1		Site inundated by impoundment.
W/BW-4-5	NO. 6 (?)	1	U 3		1	3		1	1	1	1			Several structures.

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
W/BW-4-7	No. 2	2	U 3	2	1	3		4	1	3	2	1	b	Recent subsidence (?).
W/BW-4-8 W/BW-4-11	through	4	U 2,3			2		1	1	1			b	Most sites largely reclaimed.
W/BW-4-19 W/BW-4-24	and through													
Wd/A-1-1 Wd/A-1-5	through	150	U 3		3	1	x	4	3	4	1		b	Sites similar, Reclaimed (1980).
Wd/Ca-2-1 Wd/Ca-2-4	through	180	U 3		3	1	x	4	3	4	2		b	Sites similar. Reclaimed (1980).
Wd/Nw-4-1		?	?	-	-	-	-	?	-	-	-	-	-	Unpublished records, RRCT.
Y/LE-4-50		2	U 3	3	2	1	x	4	3	3	1		a	
Y/LE-4-51		2	U 3	1	1	1	x	4	3	4	1		a	
Y/M-4-29		4	S 2			2		1	1	1	1			

Alphanum. identifier	Name	Area (ha)	Type	Open e/a	Debris	Spoil	Combustn	Leachate	Erosion	Depositn	Runoff	Recharge	Subsidnc	Other/Comment
Y/M-1-33, and	Y/M-1-34, Y/M-2-50	12	U 2	1	2	1		1	1	1	1		b	Sites similar, discussion combined.
Y/N-3-1 Y/N-3-3	and through	24	U 2,3		3	1	x	4	3	4	1		a b	Sites similar, discussion combined.
Y/N-2-7 Y/N-3-50	and and													
Y/N-1-80	Belknap Mines													

In addition to the mines described here a few others have been reported by various investigators, or are noted without site numbers or additional comments in unpublished records of the Railroad Commission of Texas. If these reports could not be confirmed in the field or were not substantiated by adequate treatment in the literature they were omitted from the present inventory. Some sites were described in sufficient detail to establish their general locations but: (1) the current field study failed to locate the sites or disclosed no recognizable impact there, and/or (2) no other record of environmental geologic conditions there could be found. Such sites also were omitted.

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