ENGINEERING GEOLOGY IN WASHINGTON

Volume I

RICHARD W. GALSTER, Chairman
Centennial Volume Committee
Washington State Section, Association of Engineering Geologists

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

BULLETIN 78

1989

Prepared in cooperation with the Washington State Section of the Association of Engineering Geologists

WASHINGTON STATE DEPARTMENT OF
Natural Resources

Brian Boyle - Commissioner of Public Lands
Art Stearns - Supervisor

Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

Engineering Geology in Washington, Volume I
Washington Division of Geology and Earth Resources Bulletin 78

Land Subsidence in Washington

TIMOTHY J. WALSH and ROBERT L. LOGAN
Washington Department of Natural Resources
Division of Geology and Earth Resources

INTRODUCTION

The occurrence of subsidence, or the lowering of the ground surface with respect to a datum plane, is classified into two broad categories: endogenic and exogenic (Prokopovich, 1979). Endogenic subsidence involves large areas of the Earth's crust and is of tectonic origin. Exogenic subsidence involves only the outermost portion of the Earth's surface and is commonly induced by man. Only exogenic subsidence will be discussed in this paper.

We investigated six types of exogenic subsidence that might occur in Washington:

- Hydrocompaction, or subsidence due to the wetting of soils
- Subsidence due to fluid withdrawal from both confined and unconfined aquifers
- Subsidence due to the degradation of organic matter
- Subsidence due to piping
- Subsidence into cavities created by dissolution
- Mining-induced subsidence

HYDROCOMPACTION

Hydrocompaction is a type of subsidence that typically occurs in loess or wind-blown silt and alongside irrigation canals or behind dams where the water table is artificially raised.

Although hydrocompaction (also called hydroconsolidation) is common in loess in most of the United States, no cases have been reported in loess in Washington (Olson, 1979). In fact, road cuts in the Palouse Formation commonly stand vertical for decades. Two principal reasons for this are: (1) the composition of the cementing agent in the loess and (2) the history of the loess since its deposition.

Montmorillonite is the primary cement in loesses of the mid-western states, whereas illite, with only trace amounts of montmorillonite, comprises the primary cement in the Palouse Formation of eastern Washington (Lobdell, 1981). The ability of montmorillonite to absorb water in its crystal lattice on wetting causes a loss of strength and results in collapse at any points of contact between grains in loess. Research shows that illite can absorb less than half the amount of water that montmorillonite can, making illite-cemented soils much less susceptible to hydrocompaction than montmorillonite-cemented soils.

Another reason why the Palouse loess is less sensitive to hydrocompaction than other loesses may be due to its environmental history. Olson (1979) attributes the stability of the Palouse Formation to the possibility that it has been subjected to previous wetting. Dry densities of 95-98 pcf (1,520-1,568 kg/cu m) at porosities of 42 to 44 percent were reported by Lobdell (1981) for Palouse loess; in contrast, mid-west loesses have dry densities of 70 to 90 pcf (1,120-1,440 kg/cu m). The relative difference in density may indicate prior compaction of Palouse loess, possibly due to wetting.

Loess in western Washington is also stable. Thorsen (1987) attributes the stability both to prior wetting and compaction by overriding glaciers.

The only hydrocompaction of any significance has occurred in coal mine spoils. A residence near Bellingham suffered foundation damage due to hydrocompaction of the mine dump from the Rocky Ridge mine. Another instance of hydrocompaction of mine spoils occurred in the town of Black Diamond, where a settlement of fill over a period of several months in 1987 caused a burn barrel to sink below the previous ground level.

FLUID WITHDRAWAL

Fluid withdrawal from confined and semiconfined aquifers can induce subsidence. Prokopovich (1975) defined two mechanisms: (1) active or quick-response subsidence which occurs in the coarser grained sediments due to a decrease in artesian head and a corresponding increase in effective load, causing a readjustment of pore pressures and rapid compaction and subsidence; and (2) residual subsidence, which occurs in the finer grained sediments due to a decrease in piezometric head; this increases the effective gravitational load and leads to dewatering into the adjacent aquifer, causing a decrease in pore pressures and gradual compaction subsidence, particularly in highly compressible sedimentary rocks. Dewatering of aquitards is accompanied by the additional stress of vertical seepage (Poland, 1981). Holzer (1984) suggests that extension

due to horizontal capillary pressure and localized differential compaction also occur and lead to surface rupture. These types of subsidence can be widespread and can result in a large lowering of ground surface. Subsidence in California's San Joaquin Valley affects 13,500 sq km and reached a maximum of 28 ft (Poland, 1981).

Subsidence due to oil withdrawal at the Wilmington oil field in southern California caused noticeable effects over an area of 41 sq km, lowered Terminal Island completely below sea level, and reached a maximum of 29 ft (Kopper and Finlayson, 1981). Many instances of subsidence due to fluid withdrawal from confined aquifers have been reported throughout the United States (Poland, 1981), but none has been reported in the state of Washington. There are currently no producing oil or gas fields in the state, and the ones that produced in the past were small (McFarland, 1983). The principal areas of ground-water mining occur in the Columbia Basin where water is withdrawn from semiconfined aquifers in flowtop breccias of Columbia River basalt and in interbedded gravel. Because the porosity in these rocks is due largely to vesiculation, pores are rigid and do not adjust to the lowering of hydrostatic pressure. Also, because the overlying and underlying basalts are dense and have extremely low porosities, ground water does not seep into the aquifer as it does from shales. Therefore, the basalt aquifers are not subject to either active or residual subsidence.

DEGRADATION OF ORGANIC MATTER

Subsidence due to organic matter degradation commonly occurs by the draining and subsequent oxidation of peaty soils, by the overloading of peaty soils, or by the use of organic matter, usually logging slash, in construction site fills.

Peaty deposits are fairly common in Washington state and, although easily recognized, still have been the sites of local but costly subsidence-induced damage. For example, a small parking lot in western Washington was recently built on a scarified peat bed and immediately began to subside. Removal of the fill material was required, at a substantial cost.

Subsidence is also known to occur where logging slash is disposed of in fill for building pads for homes or in fills for log haul roads. Within a few years the slash begins to decay, and eventually subsidence occurs, causing structural damage to houses or failure of road fills. Because burial of slash in a construction fill is unlikely to be documented, the potential for this type of failure is difficult to predict and is often only hypothesized because no other mechanism seems likely. If rotting slash is not deeply buried, however, this failure mechanism can sometimes be observed; it was noted by geologists from the Washington Division of Geology and Earth Resources in a housing development near Olympia in 1982.

PIPING

Subsidence due to piping in natural materials is rare, whereas failures along sewer lines and water mains are fairly common.

Fredricksen (1936) reported 18 in. of subsidence over an area of 320 by 325 ft in Bellingham, Washington. Although a portion of the affected area is underlain by a coal mine, the mine is located at a depth of 496 ft below the surface in a well indurated Tertiary sandstone unit. No evidence could be found within the then-active mine to suggest that mine collapse was the cause of subsidence. Deposits of fine sand at the emergence of springs from the overlying glacial unit suggested winnowing of the sand from a gravel unit overlying a relatively impermeable clay. Fredricksen concluded that the subsidence was caused by the washout of the sand matrix, suggesting that natural piping within the sand and gravel and subsequent collapse of pipes were the cause of this subsidence.

A more frequent and more significant type of subsidence due to piping, particularly in urban areas, is the outwash of fills and natural unconsolidated sediments into ruptured pipes. Sewer mains rupture for many different reasons, such as deterioration brought on by age, by the buildup of caustic acids (most notably sulfuric acid) due to inadequate flushing of sewage, or by earthquake damage. Several recent examples illustrate the seriousness of the problem.

In March of 1986 a sinkhole 40 ft across appeared in Hudson Street in Longview, Washington. The subsidence was attributed to failure of a sewer line that subsequently acted as a vacuum and sucked the fill from under the street and into the sewer. Temporary repairs were made at a cost of more than $150,000, but the sewer failed again 9 months later. Eventually 1,000 sq ft of concrete street and 75 ft of sewer line had to be replaced (The Olympian, 1986).

In another incident, 20 to 25 cy of sand and gravel was washed down a sewer line from beneath a busy street in Lacey, Washington, nearly resulting in a collapse. The cave-in was first recognizable only as a manhole-size hole in the pavement (Figure 1); however, closer examination revealed that a cavity 19 ft deep and 10 ft across had formed beneath the street. The sewer line had deteriorated as a result of attack by sulfuric acid formed from hydrogen sulfide gas being emitted by slow moving or stagnant sewage. The failure was in a 21-in. reinforced concrete pipe at a depth of 19 ft. Repair was costly, as not only did the pipe need to be relined but downstream sewage lines also had to be purged of gravel deposits. Ventilation of the lines is recommended to prevent future damage from occurring.

Figure 1. Surface expression of piping-induced cavity beneath street in Lacey, Washington. The 3-ft-diameter hole opens to a 10-ft-diameter, 19-ft-deep hole beneath a heavily travelled street. Note base of road barriers at top for scale.

One of the most spectacular incidents of sewer piping occurred in Seattle in November 1957 (Haldeman, 1986). Downwarping of a few feet of the median strip of Ravenna Boulevard was noted the first evening, but by the next morning a pit 100 ft long, 66 ft wide, and 40 ft deep occupied what had been a quiet neighborhood street. It was speculated that a 6-ft-wide sewer main located 145 ft below the street level had failed, possibly from cracking developed in the 1949 earthquake. The damaged main eventually provided a passageway for thousands of cubic yards of Quaternary glacial sediments to be flushed away. Trapped sediment and debris moved through the main, blowing manhole covers into the air, flooding homes and businesses in adjacent neighborhoods, and causing subsidence in other areas. Within 3 days the pit had grown to 200 ft in length, 175 ft in width, and 60 ft in depth. A slurry of sand and water occupied the pit floor and was eventually stabilized by using the Joosten Process of forcing a mixture of sodium silicate and calcium chloride into the slurry, causing it to harden. After a bypass was successfully completed, 17,000 cy of fill was used to plug the pit. More than $2 million was spent to rehabilitate the area.

Subsidence of this type can exact a high toll and necessitates increased maintenance on the part of municipalities. Spokane has recently launched a 7-yr program to line their entire sewer system at a cost of $2.8 million (Laughtland, 1987). Such costs pale next to the costs of damage and potential liability at a collapsed city intersection.

Broken water mains are also a common cause of subsidence, again in urban areas where repairs are usually very costly. One such failure occurred in downtown Seattle, Washington, in February 1987 (The Olympian, 1987). A hole about 50 ft wide and 8 ft deep forced closure of downtown streets and interruption of gas, power, water, and sewer service to nearby businesses. Damages were estimated to be well into six figures in one affected building alone.

DISSOLUTION

Subsidence due to dissolution occurs in rocks that are highly water soluble, such as halite or gypsum, or in rocks that are soluble in weak acids, such as limestone. Rocks of the highly water-soluble variety are rare in Washington, but limestones do occur. Many small areas of the state have developed karst topography (Figure 2), and a number of caves have formed by limestone dissolution, the largest of which, Gardner Cave, has a slope length of 1,050 ft (Halliday, 1963).

The limestone areas of Washington are mostly restricted to the sparsely populated northern part of the state, in a discontinuous belt from the San Juan Islands to the Okanogan Highlands. The other areas are either insignificantly small or are restricted to sparsely populated areas of high elevation in the Cascade Range. Because many of the limestone units consist of steeply dipping strata, their extent is usually restricted to long narrow areas. Because of the small area, pattern of exposure, and sparse population, subsidence due to limestone dissolution creates no damage to structures and generally goes unnoticed in Washington.

MINING-INDUCED SUBSIDENCE

Subsidence related to coal mining is a significant problem worldwide and constitutes the principal subsidence hazard in Washington, at least in terms of total affected acreage. Mine maps on file at the Washington Division of Geology and Earth Resources (Schasse et al., 1983) document that underground coal mine workings underlie at least 50,000 acres in western and central Washington, in both rural and urban areas. Additional acreage is affected by small mines and prospects for which there are no records. Outcrop and shallow subsurface geologic data are sufficient to estimate coal reserves for an area in Washington of approximately 250,000 acres (Figure 2). Although most of this area is not underlain by mines or prospects, it represents the maximum potential extent of mines and prospects.

The types of subsidence that occur depend on the method of mining and on the character of the coal deposit. Therefore, evaluation of subsidence requires an understanding of the historical development of the mines and mining methods in order to predict where areas of instability may lie.

Coal Mining Methods

Coal mining methods used in Washington are summarized by Evans (1912), Green (1943), and Magill and Associates (1979), from whom the following discussion is drawn. In the early days of mining, coal was usually

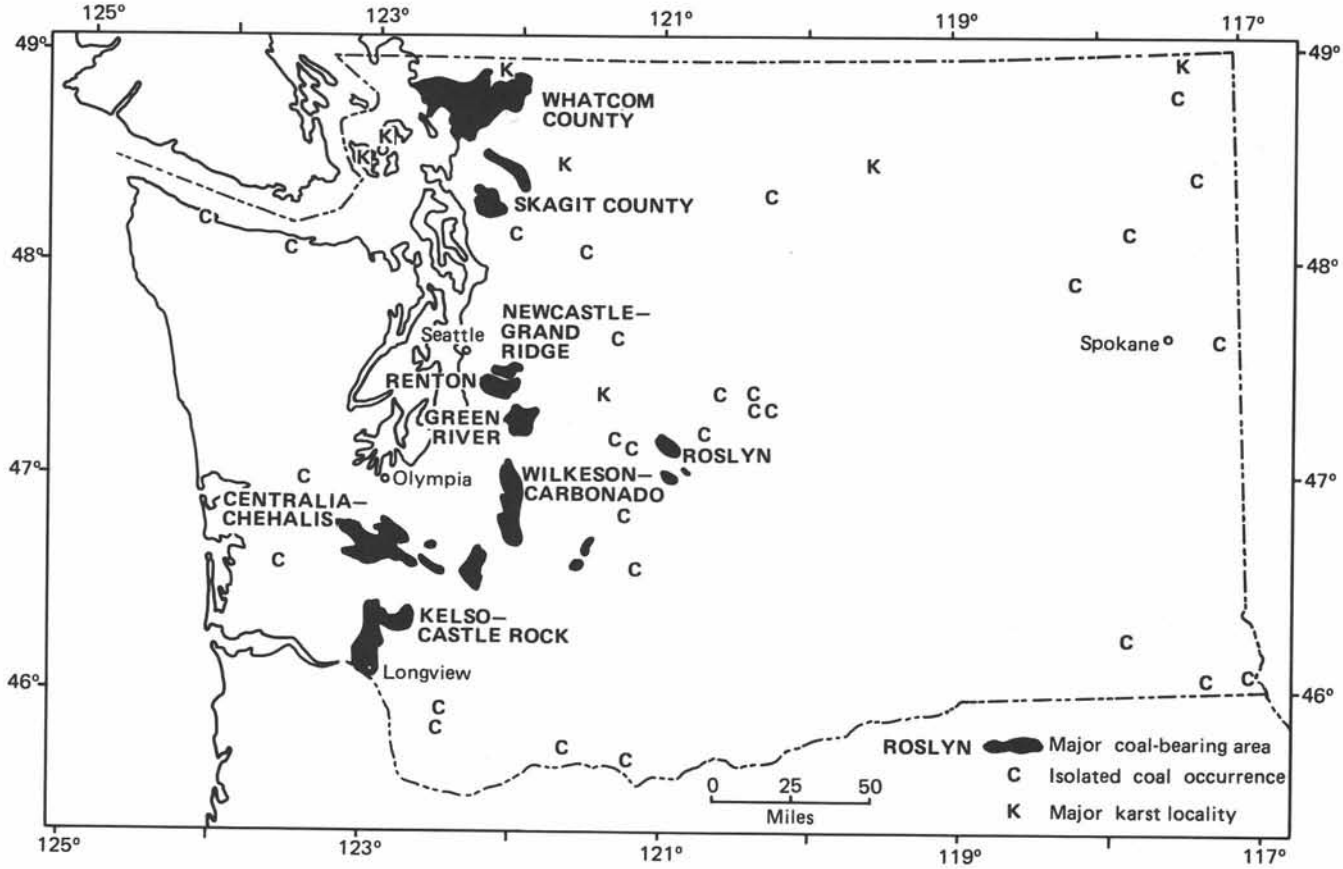

Figure 2. Coal-bearing areas of Washington and areas of karst topography. Modified from Beikman et al. (1961) and Halliday (1963).

accessed by a water-level drift driven into a hillside from a stream valley. The drift had a slope toward the stream of less than one degree to facilitate drainage and to allow loaded cars a downslope trip and empty cars the upslope trip. The drift was driven approximately at the top of the static water level and allowed the mine to be self-draining. Only coal topographically higher than the drift could be worked by this method, so drift mines, or water-level mines, were usually limited to one or two levels.

Once coal was worked out of the drift mine, the coal usually had to be mined from a slope. A slope was driven on the full dip of the coal seam unless the seam dipped more steeply than approximately 50 degrees, in which case an oblique slope was driven. In larger mines, a companion slope was also driven for air circulation. At some mines, in order to have the mine entry in an advantageous location to load the coal (such as on tidewater or at a railroad), the slope was reached through a rock tunnel. Rock tunnel entries were also used to reach the coal seam subcrop beneath glacial deposits and to access coal downdip of older mine workings.

Coal in Washington has traditionally been mined by the methods of room and pillar (also known as breast and pillar), chute and pillar, and by booming. Longwall methods have been attempted in several mines but were not successful. Figure 3 shows the terms in use locally for various features of underground mines.

The room and pillar method is used in shallowly dipping coal seams. Nearly horizontal gangways are driven along the strike of the coal seam; a parallel tunnel updip is called the counter. The gangway is a haulage tunnel, and the counter is a return airway. Every 40 to 70 ft along strike, the two tunnels are connected by chutes from 4 to 10 ft wide. Updip of the counter, the chute is widened into a room (called a breast in more steeply dipping seams); coal is left between the rooms in blocks called pillars. In chute and pillar mining, chutes as much as 12 ft wide are driven up the dip, blocking out larger pillars. In both methods, pillars are eventually removed by cutting off slices or skips. If pillars can be completely removed (complete extraction), thereby eliminating all support, the roof can be collapsed, resulting in nearly immediate but even, controlled subsidence. If parts of the pillars must be left (partial extraction), the eventual subsidence may be postponed for decades, and the timing cannot be predicted (Kratzsch, 1986). A third method of mining used in Washington is a variant of either of the above, called booming. It is used where the coal seam is too thick for the roof to be securely tim-

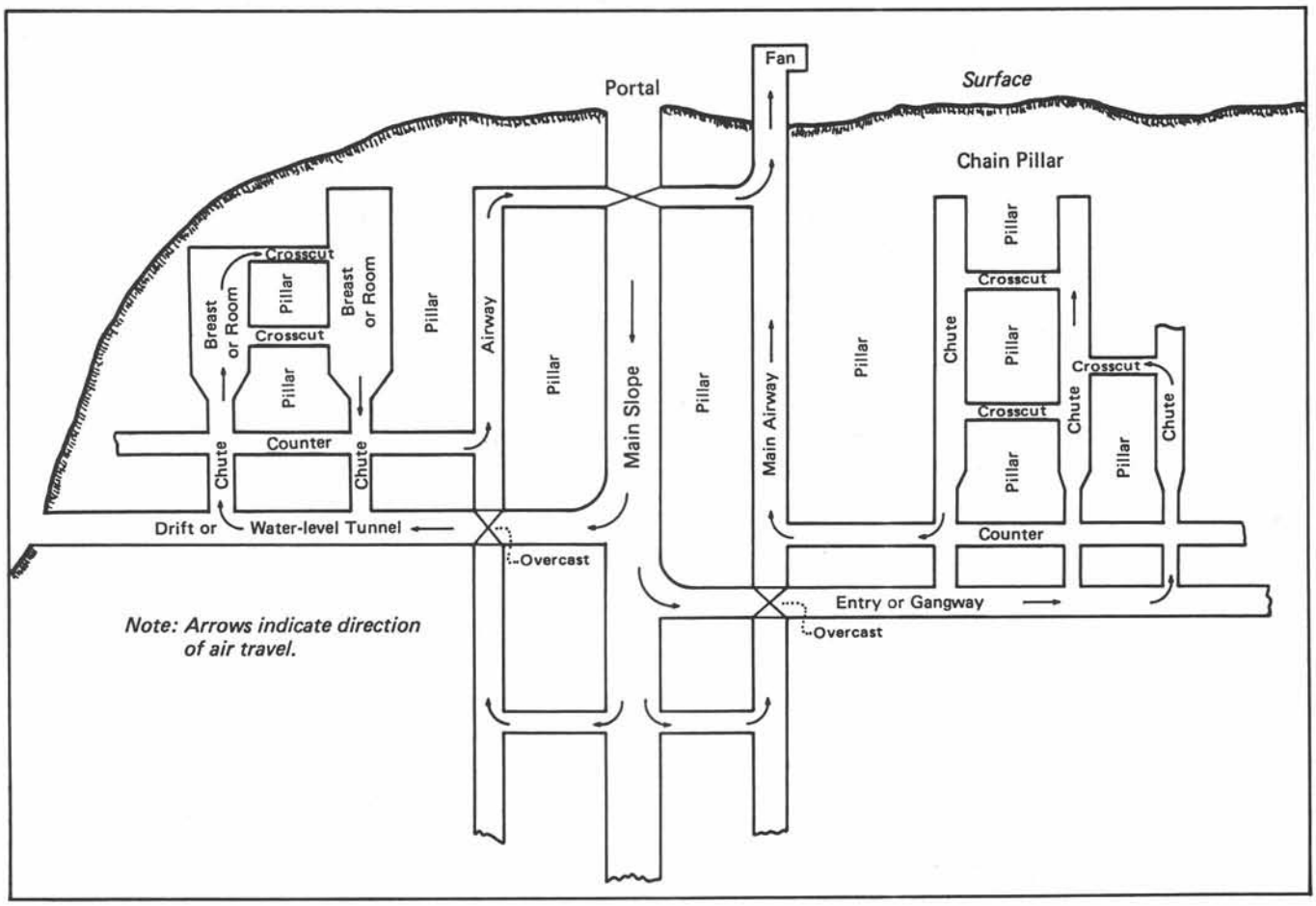

Figure 3. Diagram of features of underground coal mines and terminology in use in Washington. Modified from Green (1943).

bered (Green, 1943). In this method, the coal is shot from the pillar with explosives, and the roof is supported only by low wooden bulkheads to prevent complete collapse. This method frequently led to uncontrolled subsidence.

Coal was mined either while advancing or retreating. If mined on advance, pillars were blocked out, and skips were taken as the working face was extended. In retreat mining, the mine was developed to its maximum extent, and the pillars were blocked out and pulled from the outside in. This allowed for greater recovery, but if economic conditions forced the shutdown of a mine already blocked out for retreat mining, it would be abandoned with pillars remaining, which would leave only partial roof support that was not designed for permanent use.

Types of Coal Mine Subsidence

We include under coal mine subsidence both areal subsidence, or the general sagging of the ground surface, and cave-ins. Subsidence into a coal mine can occur in several ways. If the roof is weak, it will fall in blocks and leave a rubble on the floor. Successive roof falls occur until the void is filled. Because the rubble has a greater bulk than the undisturbed roof rock, the volume of roof fall necessary to fill the void is less than the volume of original void, and the maximum subsidence is less than the vertical extent of the mined horizon. Because the bulking factor depends on the shape, size, amount of rotation, and strength of overburden rock (Dunrud, 1984), prediction of subsidence depends on detailed information about the overburden. The maximum thickness of an individual roof fall is controlled by the vertical and horizontal dimensions of the void, and also by the shape, but is typically between 70 percent and 95 percent of the thickness of the coal seam for a single roof fall (Kratsch, 1983). If the roof fall remains on the floor, the void will be filled by a few roof falls, and the overburden will be partially supported. Above this, the overburden will sag but will break no further. In some mines, however, the roof fall occurs above a slope or above a steeply dipping floor. If the surface is steep enough, the rubble will continue to slough downslope, and the roof fall can stope to the surface, regardless of

the thickness of overburden. Subsidence also can reach the surface from deeper voids if more than one seam is mined. Then the subsidence can be additive. If the void is very close to the surface, the entire overburden can collapse at once. This is called a crop fall.

Subsidence can occur by the plunging of a pillar into an incompetent underclay. This results in uplift of the floor adjacent to the pillar into the void space.

Pillars can also fail by crushing, since they bear the entire lithostatic load over a smaller area than was the case before mining, and they are laterally unsupported.

The surface expression of these types of subsidence depends on the physical properties of the overburden but is generally of two types, trenches and pits or sinkholes. Pits characteristically form above roof failure of a room or breast, and trenches form above failed pillars (Gray and Bruhn, 1984).

Another type of subsidence associated with underground coal mines is the failure of slope entries and airways or the fills with which they were plugged. Tree stumps and car bodies are commonly dumped into steeply dipping tunnels to anchor fills that are then merely bulldozed into the hole. Inevitably, the anchors will slip downslope or the tree stumps will rot, although the failure may be postponed for a generation.

Coal Mining in Washington

Although it was discovered much earlier, coal was first mined near Bellingham in 1853 (Beikman et al., 1961). In 1854, mines were opened near Renton and Issaquah, and by 1887 coal mining was a major industry in Washington Territory, with mines also operating in the Skagit River valley, near the towns of Roslyn and Cle Elum in central Washington, in the vicinity of Black Diamond in King County, and near Wilkeson and Carbonado in Pierce County (Figure 2). In 1887, the first report was published by the newly established office of the Territorial Mine Inspector. Initially, the powers of the office were limited, and it was not until the turn of the century that detailed mine maps began to be filed with the mine inspector. Eventually, all mine operators filed annual progress maps at a scale of 1 in. = 100 ft. This map collection, numbering more than 900 maps, is housed at the office of the Washington Division of Geology and Earth Resources (Schasse et al., 1983). These maps constitute an invaluable source of geological and engineering data on the coal resources of Washington, but they do not cover the first half-century of the coal mining industry, when more than 20 million tons of coal were taken from underground mines.

The coal fields of the state that are most important in a discussion of urban mine subsidence are Whatcom County, Newcastle-Grand Ridge, and Renton (Figure 2). Other coal fields, such as Wilkeson-Carbonado, Roslyn, and Centralia-Chehalis (Figure 2) are responsible for considerable subsidence but are largely located in rural areas. There also are numerous smaller coal areas that can cause localized subsidence hazards.

Whatcom County Area

The Whatcom County area consists of scattered coalfields of varyied sizes, isolated from each other by cover of glacial drift. The largest and most important of these is the Bellingham field. There have been two mines and several prospects in this field, dating to the discovery of these coal measures in 1852 by a Captain Pattle. Pattle and two partners located and later sold claims in the south part of Bellingham, but their work never resulted in a commercial mine (Jenkins, 1923). In 1853, two loggers named Brown and Hewitt discovered a seam of coal in the roots of an uprooted tree at what was then called Sehome, and it was this discovery that led to the first mine (Landes, 1902). The Bellingham Bay Coal Company was created to mine the seam, which was named the Bellingham #1. The entry to the mine was located at what is now the corner of Myrtle Street and Railroad Avenue (Jenkins, 1923). No map of the mine is available, but the narrative descriptions of Goodyear (1877) and Watson (1887) permit reconstruction (Figure 4). Because this reconstruction is only approximately located, areas of potential subsidence are poorly known. It is also not known how near the surface the mine was worked. Jenkins (1923) reported that the barrier pillars left to support the surface were only 20 ft thick, but the thickness of glacial deposits overlying the coal measures is unknown. Because recessional glacial outwash will have less strength than the Eocene sandstones overlying the coal, the thickness of these deposits is important for delineating areas of subsidence risk.

Jenkins (1923) reported that there was considerable trouble with subsidence that required concrete arches to support buildings, particularly near the intersection of Holly Street and Railroad Avenue. Subsidence-induced structural damage has been noted in a number of older buildings above the mine, but newer construction is unaffected (Tetra Tech, Inc., 1984). Whether this implies that there is no remaining void space associated with the mine is not known.

In 1918, a new mine was opened on the Bellingham #1. It operated almost continuously until 1955, with a total production of about 5-1/4 million tons of coal (LaSalata et al., 1985). Figure 4 shows the locations and elevations of the main passageways of the mine. Subsidence has been reported at several sites over the mine, although the workings are deeper than would normally be thought of as capable of producing surface effects. These subsidences have not been investigated in detail, and there is some question as to whether they are truly mine-related (Batchelor, 1982; Tetra Tech, Inc., 1984). Nonetheless, there are significant areas overlying the mine which are probably unstable and capable of producing surface effects.

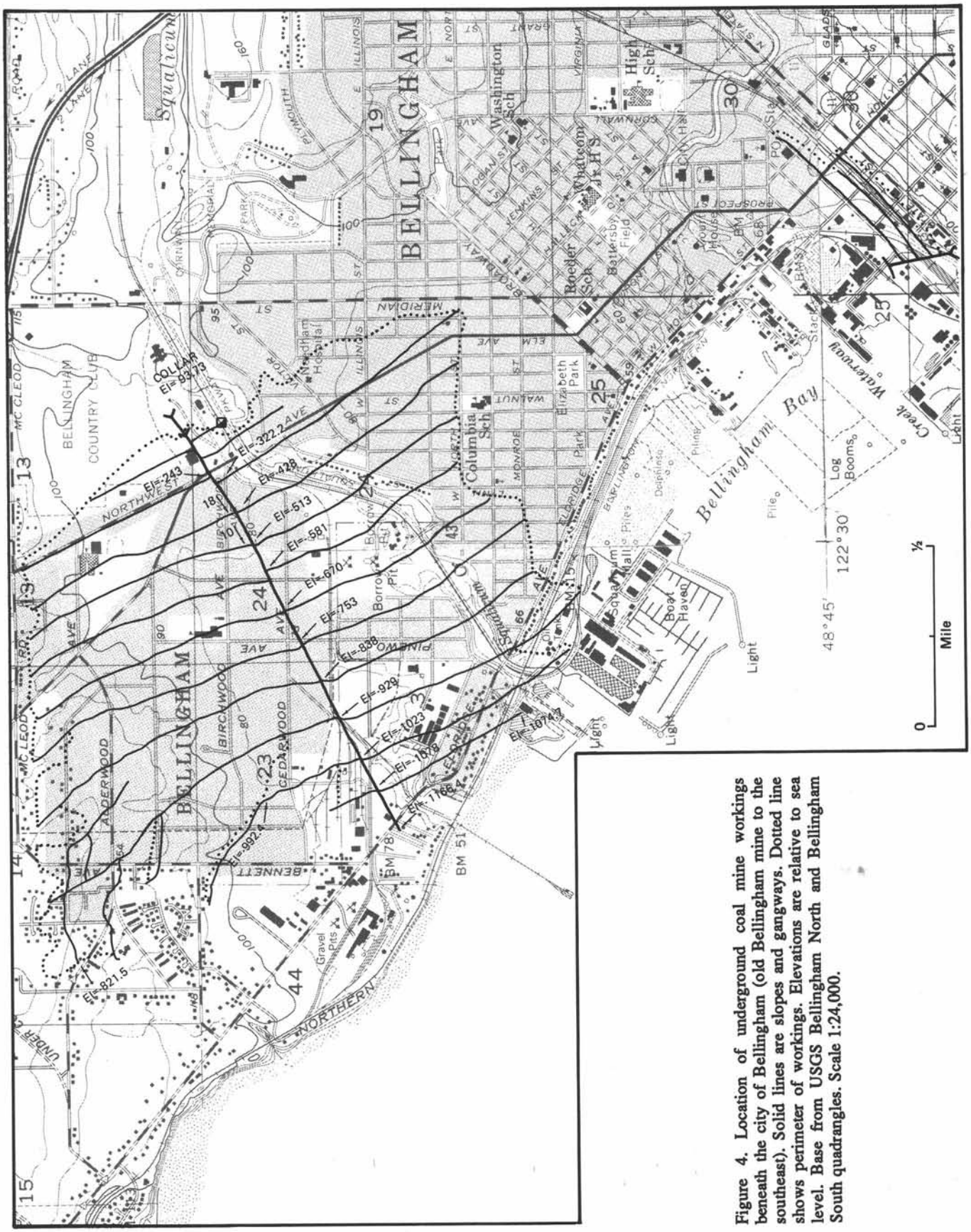

Figure 4. Location of underground coal mine workings beneath the city of Bellingham (old Bellingham mine to the southeast). Solid lines are slopes and gangways. Dotted line shows perimeter of workings. Elevations are relative to sea level. Base from USGS Bellingham North and Bellingham South quadrangles. Scale 1:24,000.

Renton Area

Mining began in the Renton area in 1853 (Phillips and Walsh, 1981), but most of the early mining was at a small scale. In 1874, the only large mine in the area was opened; the Renton mine, which underlies a large portion of the city (Figure 5), operated until 1922. The earliest workings were reached by a slope on the side of Renton Hill. The bulk of the coal was removed via a rock tunnel which bypassed the earlier slope. This mine was developed on a seam called the Renton #3. Two other seams, #2 and #1, overlie the #3 at stratigraphic intervals of approximately 85 and 195 ft respectively (Evans, 1912). Only small mines were developed on these seams, but the workings overlie those of the main Renton mine and pose the problem both of additive subsidence and additional area underlain by shallow mine workings. Mine maps for this area show the workings through 1922 but are badly damaged, making location of subsurface features suspect. Additionally, third mining or pillar robbing was done in this area at least through 1948 (LaSalata et al., 1985), but we have no maps of this.

Subsidence has been noted in Renton at least since 1965 (Mullineaux, 1965) and continues through the present (Table 1). Morrison-Knudsen Co., Inc. (1985) found six areas in Renton where subsidence had occurred. These included crop falls and fill failures, and one was a composite failure probably caused by ground water piping into a mine void, causing a loss of fill material into the mine.

Newcastle-Grand Ridge Area

The first mine in this area was located in the hillside just west of Issaquah in 1854 but was soon closed due to an Indian uprising (Phillips and Walsh, 1981). Later workings were opened to the west at Newcastle (Figure 6) and to the north along Grand Ridge, as well as at Issaquah (Figure 7). The only urban development in this area occurs over the Issaquah mines, and many of the original entries to the mines have been covered. A recent survey, however, reported 25 sites where subsidence was visible (Goodson and Associates, 1984). At least eight of these subsidences occurred since 1966. Most of these are in the Wildwood subdivision and are probably caused by crop fall into a water level entry that was abandoned in the 1950s. Although the damage from these subsidences has been slight, there is the potential for serious injury, and at least one cave-in was nearly disastrous. In 1967, a water-level tunnel collapsed in a newly terraced lot. Two children playing in the hole were overcome by lack of oxygen; their father and two policeman were also overcome in attempting to rescue the children. All were finally saved by firemen with oxygen equipment (Gilley and Collaizi, 1970). Although the main problem was dead air (lack of oxygen), physicians who treated the victims reported traces of methane in their lungs (Thorsen, 1987).

Many of the mine openings were filled and drainages were altered during the development of housing in this area and the quality of closures is not known (Goodson and Associates, 1984). It is likely that failure of these closures will lead to future subsidences in Issaquah.

Table 1. Mine-subsidence reclamation projects performed by OSMRE since enactment of SMCRA, 1977-1988. Failure types: 1, failure of fill in a shaft, slope, or rock tunnel; 2, cave-in due to roof fall; 3, sag due to roof fall; 4, hydrocompaction of spoil.

Project name	Mine name	Location	Date	Failure type
Engel	Wonder	SW/4 28(22-7)	2-79	2
Bevan	Burnett	S/2 16(19-6)	6-79	2
Campbell	Burnett	S/2 16(19-6)	5-81	1
Burdic	Wonder	SW/4 28(22-7)	9-81	1 or 2
Lake Whatcom	Rocky Ridge	SW/4 31(38-4)	11-82	2
Noorani	Denny-Renton	SW/4 17(23-5)	11-82	1
Gatto	Burnett	S/2 16(19-6)	2-82	1
May Creek	May Valley	SE/4 2(23-6)	6-82	2?
Beacon Hill	Beacon Hill	NE/4 14(23-4)	1-84	2
New # 12	New # 12	S/2 12(21-6)	1-84	1
Diamond	Diamond	SW/4 13(23-4)	7-84	1?
Davis	Davis	NW/4 14(21-7)	6-85	1
Denny-Renton	Renton	NW/4 20(23-5)	3-86	3?
Scott	unknown	NW/4 28(19-6)	5-87	1
Grgurich	#2	NE/4 14(21-6)	5-87	4
Koch	Rocky Ridge	SW/4 31(38-4)	9-87	4
Waterhouse	Waterhouse	NE/4 28(24-5)	2-88	1

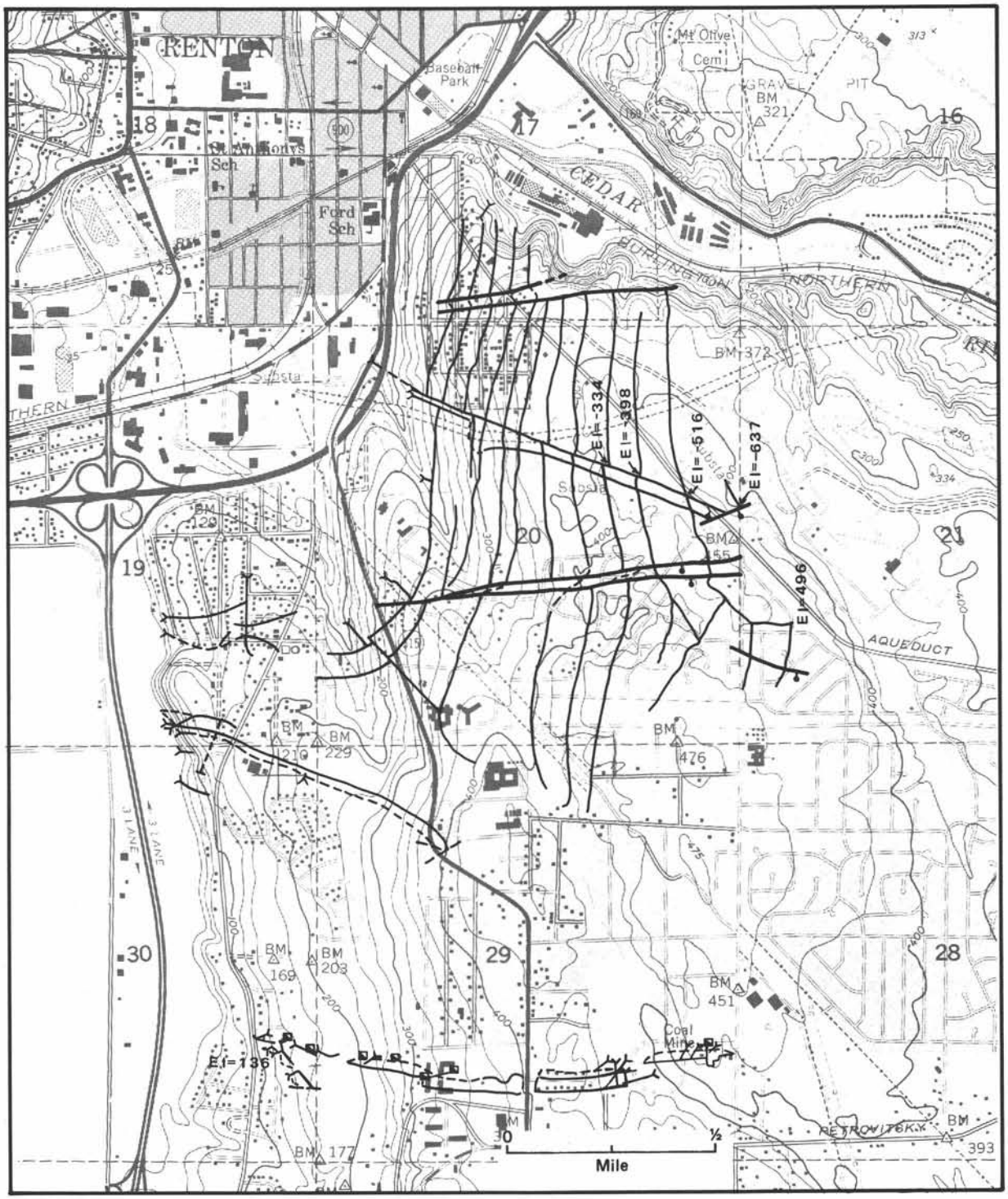

Figure 5. Location of underground coal mine workings in the vicinity of the City of Renton. Solid lines are slopes and gangways; dashed lines are rock tunnels; dotted lines are the perimeter of mine workings. Faults are shown as bolder line. In the main Renton mine, workings on upper coal seams are left off for clarity. Base from USGS Renton quadrangle. Scale 1:24,000.

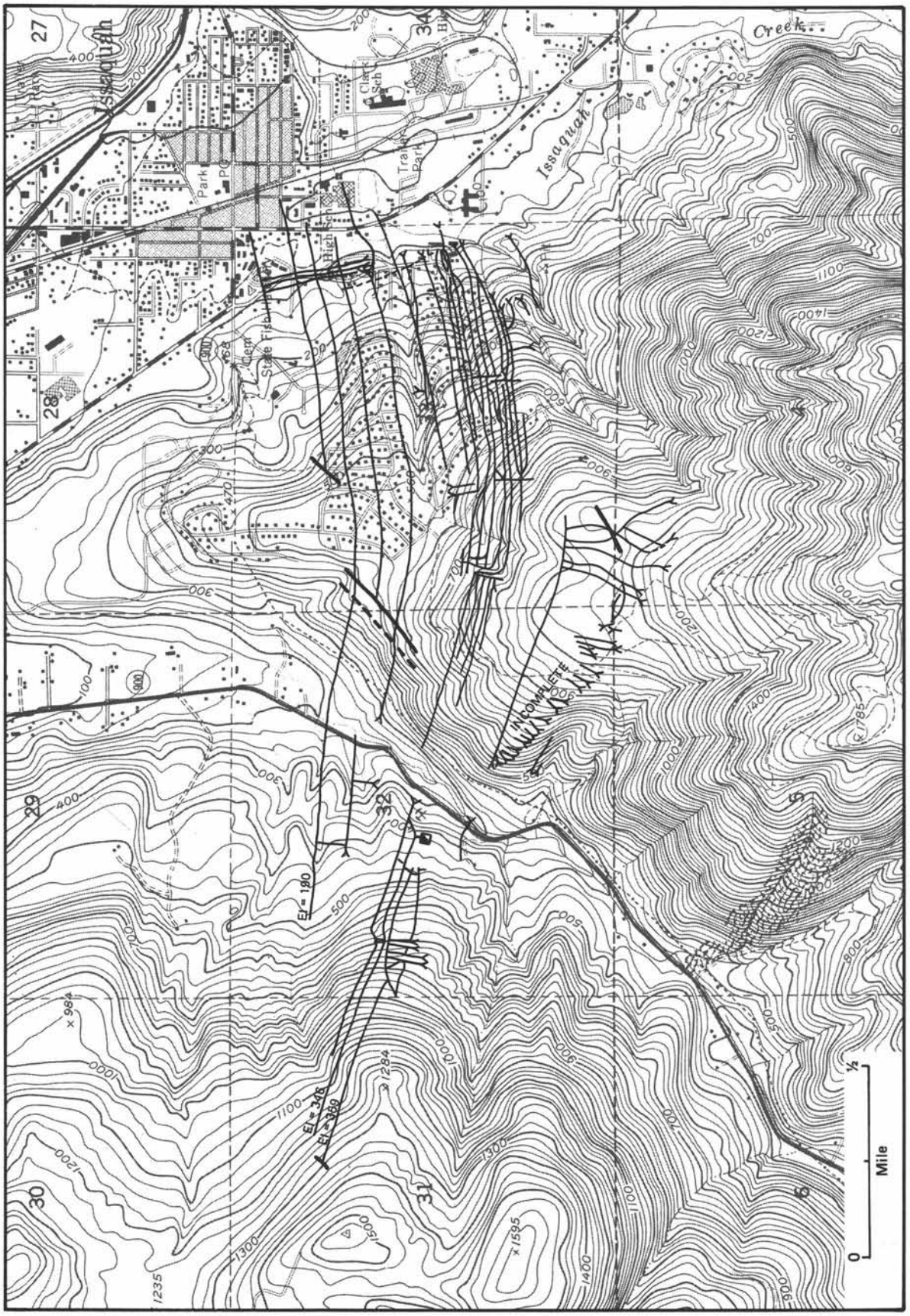

Figure 6. Location of underground coal mine workings in the Newcastle coalfield, located between the cities of Bellevue and Issaquah. Solid lines are slopes and gangways; dashed lines are rock tunnels; bolder lines are faults. Base from USGS Issaquah and Mercer Island quadrangles. Scale 1:24,000.

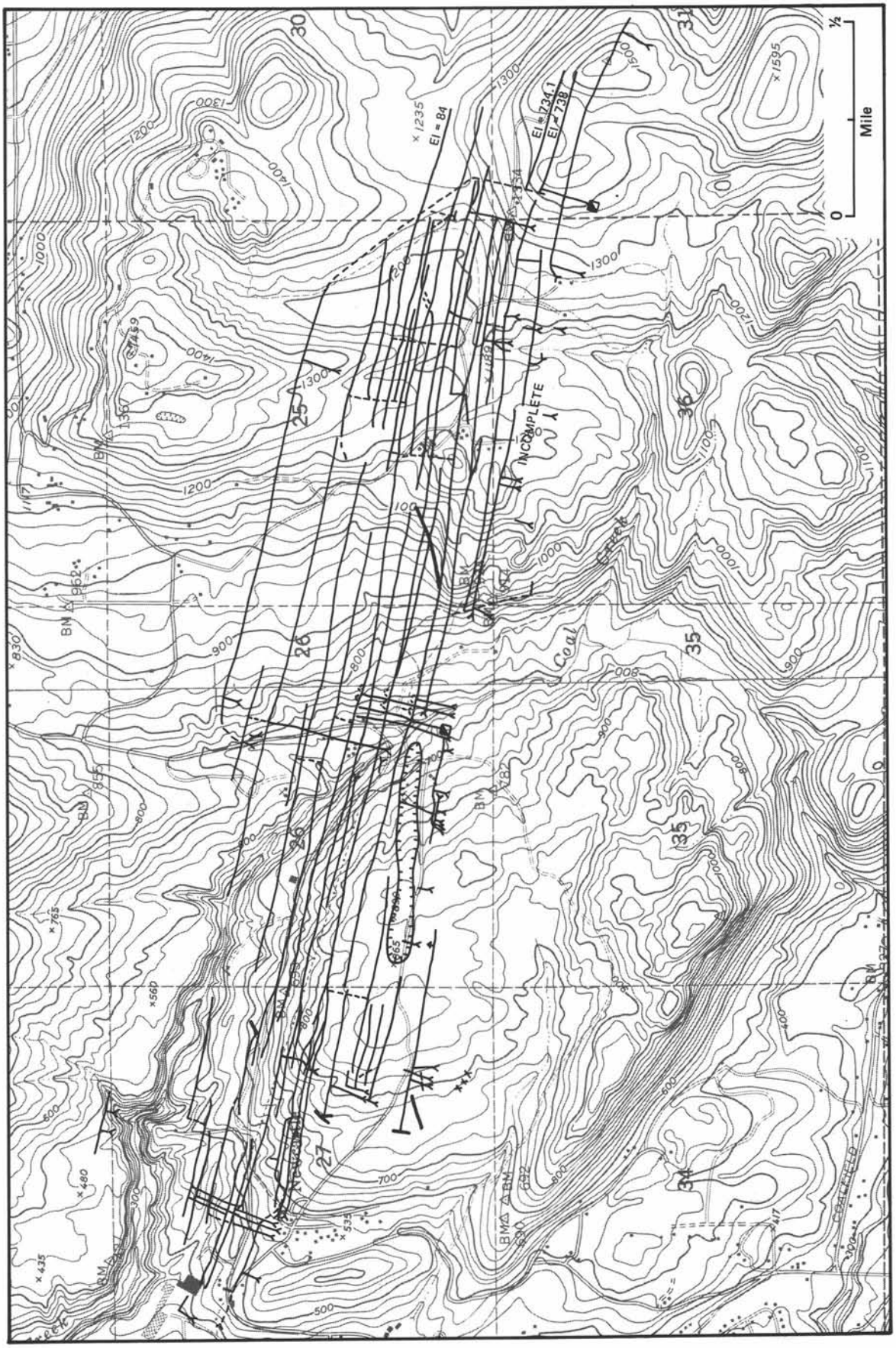

Figure 7. Location of underground coal mine workings near the city of Issaquah. Solid lines are slopes and gangways. Bolder lines are faults. Elevations are relative to sea level. Base from USGS Issaquah quadrangle. Scale 1:24,000.

Subsidence over the Newcastle mines is more readily apparent than at Issaquah; a recent survey of this area revealed 166 mine entries, airways, and subsidences (Skelly and Loy Engineers-Consultants, 1985). Mine features are more visible in part because the area has not yet been developed, in part because the coal measures have an average dip of 47 degrees and are above water level through much of the area. Because the slopes are steeper than the angle of repose, roof fall above slopes sloughs into the mines, particularly when wetted. The principal hazards at these mines are the many slopes and air shafts that remain open (Skelly and Loy Engineers-Consultants, 1985) but considerable void space remains and future development must be carefully planned not only to avoid unstable ground but also to avoid raising the water level. In steeply dipping coal measures, friction across joint surfaces normal to bedding is increased, providing a measure of stability (Dunrud, 1987). Saturating these joints may provide enough lubrication to destabilize the roof rock and cause subsidence. Urbanization is encroaching on the Newcastle field, however, resulting in increased subsidence hazard. Recently, an abandoned prospect (Waterhouse prospect, Table 1) collapsed catastrophically beneath a house at the westernmost end of the field, damaging the house and its plumbing (Walsh, 1988).

Subsidence at the Grand Ridge mines is readily apparent in the vicinity of the entries but does not threaten any structures. There are housing developments in the vicinity, but much of the subsidence area lies beneath a main power line and development is unlikely in the near future. The northernmost part of the Grand Ridge area does contain a few homes, but these are stratigraphically below the mines. Planning for future development needs to take the mines into consideration because there are visible voids in the area (LaSalata et al., 1985) and further subsidence is possible.

Wilkeson-Carbonado Area

Subsidence in the Wilkeson coal field was first reported in 1923 (Knuppe and Sisson, 1923) and continues today. As recently as May 1987, shallow, undocumented mine workings collapsed in the back yard of a home to the west of Wilkeson and were fenced off prior to permanent reclamation (Table 1, Scott project). Most of the mine workings in this area are located in forested land and do not threaten any structures. The greatest hazards in the Wilkeson-Carbonado area are the open slopes, airways, and cave-ins into slopes and airways into which unwary hikers could fall.

Centralia-Chehalis Area

Coal was first mined in the Centralia-Chehalis area in the 1870s (Snavely et al., 1958), and workings were usually very shallow, due to gentle structure, poor roof conditions, and the economic limitation imposed by the low quality of the coal. Most of this coal field lies outside of the cities of Centralia and Chehalis, and older and current surface mines have removed the barrier pillars above some mines, leaving no subsurface voids.

There are some areas of mining within the city limits that have resulted in subsidence, most notably in Chehalis (LaSalata et al., 1985), but these are not well documented.

Roslyn-Cle Elum Area

Mining in the Roslyn area commenced in 1887 and continued through 1963. Extraction efficiency was considerably higher than in the western Washington coal fields, averaging 80 percent (Beikman et al., 1961). This results in much less roof support and earlier and more complete collapse. Voids can still be found in this coal field, and subsidence features are abundant, particularly near mine entries (Walker and Shideler, 1984; LaSalata et al., 1985). Most of the subsidence features are in forest or farmland and do not threaten any structures, although the towns of Ronald, Roslyn, and Cle Elum overlie old mine workings.

Miscellaneous Occurrences

Many small, isolated occurrences of coal exist in Washington (Figure 2). Some were mined commercially, but most were abandoned after limited shallow prospecting. These can be very troublesome because they were not likely to have been well shored; however, because of the small load carried above the void, they may not collapse for decades and usually not until a house is built on site (Figure 8). Nine of the 17 subsidences investigated since 1978 (Table 1) have been of this type.

Remediation

In 1977, Congress enacted Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA), which provided, among other things, for the closure of abandoned underground mine openings, reclamation of coal mine-induced subsidence, and the amelioration of mine-related hazards. Funds for this work are provided by a tax on active coal mines at a rate ranging from 10 to 35 cents/ton, depending on coal rank. The act established an agency, the Office of Surface Mining Reclamation and Enforcement (OSMRE), to administer the provisions of SMCRA.

In Washington, mine reclamation is achieved by OSMRE in two ways:

(1) Emergencies, which are defined as recent, sudden events, are reclaimed on a first priority basis. These are most commonly subsidences but have included gas flows caused by a drop in hydrostatic pressure in a mine void during dry weather.

(2) Existing mine hazards were inventoried, and priorities for reclamation were established on a nationwide basis. These include sudden subsidences that have been fenced and thus are not in need of rapid reclamation.

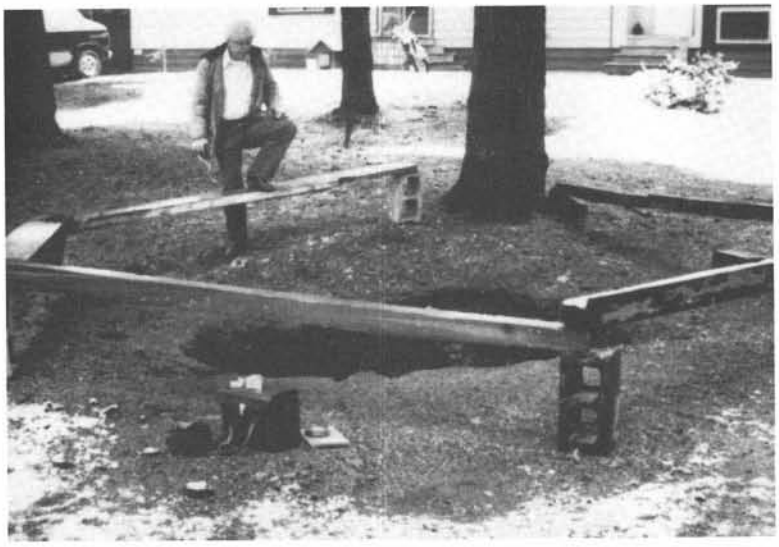

Figure 8. Cave-in over shallow mine workings. This subsidence into the Wonder mine, a small, poorly documented drift mine near Ravensdale, occurred in 1979 at the Engel home (Table 1). In 1981, a similar cave-in occurred about 1,000 ft to the north.

Funds for reclamation are allocated to those states with a federally approved surface mine regulatory program. States without such programs, such as Washington, receive funding at the discretion of the Secretary of the Interior to be expended directly by OSMRE. At present, OSMRE's reclamation expenditures in Washington are on the order of $750,000 annually. Reclamation of existing priority sites has been accomplished principally in the Roslyn-Cle Elum area, in the Newcastle coalfield, and the Wilkeson-Carbonado area. Emergency reclamation has been necessary about twice a year, chiefly for subsidence. Subsidence reclamation is summarized in Table 1.

Emergency reclamation typically is accomplished within a few weeks, but funding is available only for actual subsidence, not for repairing structural damage caused by subsidence. For this reason, prompt attention must be given to suspected coal mine subsidence before it causes damage, and contractors should consider the likelihood of future subsidence when building in areas of historic coal mining.

Local planning can help ease the potential impact of subsidence; planners are aware of mine-related hazards and can recommend construction techniques for areas affected by coal mines. King County, which has large areas underlain by abandoned coal mines, requires developers of lands designated as Coal Mine Hazard Areas to perform geotechnical studies in order to obtain building permits. King County Code 21.54.190 specifies that these studies must identify and quantify:

"1. existing underground voids resulting from previous mining activity;

"2. location and definition of all surface openings resulting from previous mining activity;

"3. location of all concentrations of lethal or noxious gases and groundwater within abandoned mine workings; and

"4. location, depth, and characteristics of all mine tailings on the surface of the site."

Any building permit issued requires, among other things, that all openings be sealed and all voids beneath building sites that present significant risk to human health, safety, and welfare be filled or otherwise remedied.

ACKNOWLEDGMENTS

Discussions with C. R. Dunrud (U.S. Geological Survey) were valuable in applying subsidence theory to steeply dipping coal seams. G. W. Thorsen (Washington Division of Geology and Earth Resources) provided valuable insights into many aspects of subsidence.

REFERENCES

Batchelor, C. F., 1982, *Subsidence Over Abandoned Coal Mines–Bellingham, Washington* [M.S. thesis]: Western Washington University, Bellingham, WA, 122 p.

Beikman, H. M.; Gower, H. D.; and Dana, T. A. M., 1961, *Coal Reserves of Washington*: Washington Division of Mines and Geology Bulletin 47, Olympia, WA, 115 p.

Dunrud, C. R., 1984, Coal Mine Subsidence–Western United States. In Holzer, T. L. (editor), *Man-Induced Land Subsidence*: Geological Society of America Reviews in Engineering Geology, Vol. 6, pp. 151-194.

Dunrud, C. R., 1987, Personal communication, U.S. Geological Survey, Denver, CO.

Evans, G. W., 1912, *The Coal Fields of King County*: Washington Geological Survey Bulletin 3, Olympia, WA, 247 p.

Fredricksen, C. S., 1936, Ground Subsidence at Bellingham Coal Mine: *Northwest Science*, Vol. 10, No. 4, pp. 6-7.

Gilley, J. E. and Collaizi, G. J., 1970, *Investigation of Coal Mine Subsidence Problem at Issaquah, Washington*: U.S. Bureau of Mines unpublished report, Washington, DC, 22 p.

Goodson and Associates, Inc., 1984, *Abandoned Coal Mine Survey in the Area of Issaquah, King County, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 77 p.

Goodyear, W. A., 1877, *The Coal Mines of the Western Coast of the United States*: A. L. Bancroft and Company, San Francisco, CA, 153 p.

Gray, R. E. and Bruhn, R. W., 1984, Coal mine subsidence–Eastern United States. In Holzer, T. L. (editor), *Man-Induced Land Subsidence*: Geological Society of America Reviews in Engineering Geology, Vol. 6, pp. 123-149.

Green, S. H., 1943, *Coal and Coal Mining in Washington*: Washington Division of Mines and Mining Report of Investigations 4, Olympia, WA, 41 p.

Haldeman, P., 1986, The great Ravenna cave-in: *Washington–The Evergreen State Magazine*, Vol. 3, No. 1, pp. 150-151.

Halliday, W. R., 1963, *Caves of Washington*: Washington Division of Mines and Geology Information Circular 40, Olympia, WA, 132 p.

Holzer, T. L., 1984, Ground failure induced by ground-water withdrawal from unconsolidated sediment. In Holzer, T. L. (editor), *Man-Induced Land Subsidence*: Geological Society of America Reviews in Engineering Geology, Vol. 6, pp. 67-105.

Jenkins, O. P., 1923, *Geological Investigation of the Coal Fields of Western Whatcom County, Washington*: Washington Division of Geology Bulletin 28, Olympia, WA, 135 p.

Knuppe, L. M. and Sisson, H. A., 1923, *Subsidence Resulting From Coal Mining Operations in the State of Washington* [B.S. thesis]: University of Washington, Seattle, WA, 72 p.

Kopper, W. and Finlayson, D., 1981 Legal aspects of subsidence due to well pumping: *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers*, Vol. 107, No. IR2, pp. 137-149.

Kratzsch, H., 1983, *Mining Subsidence Engineering*: Springer-Verlag, New York, NY, 543 p.

Kratzsch, H., 1986, Mining subsidence engineering: *Environmental Geology and Water Sciences*, Vol. 8, No. 3, pp. 133-136.

LaSalata, F. V.; Menard, M. C.; Walsh, T. J.; and Schasse, H. W., 1985, *Inventory of Abandoned Coal Mines in the State of Washington*: Washington Division of Geology and Earth Resources Open File Report 84-6, Olympia, WA, 42 p.

Landes, H., 1902, *The Coal Deposits of Washington*: Washington Geological Survey Annual Report for 1901, Vol. 1, Pt. 4, Olympia, WA, pp. 41-65.

Laughtland, J. G., 1987, Personal communication, Spokane Public Works Department, Spokane, WA.

Lobdell, G. T., 1981, Hydroconsolidation potential of Palouse Loess: *Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers*, Vol. 107, No. GT6, Proc. Paper 16309, pp. 733-742.

McFarland, C. R., 1983, *Oil and Gas Exploration in Washington, 1900-1982*: Washington Division of Geology and Earth Resources Information Circular 75, Olympia, WA, 119 p.

Magill and Associates, 1979, *Annotated Bibliography of Source Materials in Locating Abandoned Coal Mine Problems in the State of Washington*: Prepared for U.S. Office of Surface Mining, Denver, CO, and Washington Division of Geology and Earth Resources, Olympia, WA, 84 p.

Morrison-Knudsen Company, Inc., 1985, *Engineering Investigation for the Renton Area, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 64 p.

Mullineaux, D. R., 1965, *Geologic Map of the Renton Quadrangle, King County, Washington*: U.S. Geological Survey Geologic Quadrangle Map GQ-405, 1 sheet, scale 1:24,000.

Olson, B. E., 1979, Loess soils in Southeastern Washington: *Journal of the Geotechnical Engineering Division Proceedings of the American Society of Civil Engineers*, Vol. 105, No. GT6, pp. 786-791.

Phillips, W. M. and Walsh, T. J., 1981, Coal Geology of King County, Washington: *Washington Geologic Newsletter*, Vol. 9, No. 2, pp. 1-11.

Poland, J. F., 1981, Subsidence in United States due to groundwater withdrawal: *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers*, Vol. 107, No. IR2, pp. 115-135.

Prokopovich, N. P., 1975, Past and Future subsidence along San Luis Drain, San Joaquin Valley, California: *Bulletin of the Association of Engineering Geologists*, Vol. 12, No. 1, pp. 1-22.

Prokopovich, N. P., 1979, Genetic classification of land subsidence. In Saxena, S. K. (ed.), *Evaluation and Prediction of Subsidence*: American Society of Civil Engineers, New York, NY, pp. 389-399.

Schasse, H. W.; Koler, M. L.; and Herman, N. E., 1983, *Directory and User's Guide to the Washington State Coal Mine Map Collection*: Washington Division of Geology and Earth Resources Open File Report 83-8, Olympia, WA, 110 p.

Skelly and Loy Engineers-Consultants, 1985, *Abandoned Coal Mine Survey Coal Creek, King County, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 66 p.

Snavely, P. D., Jr.; Brown, R. D., Jr.; Roberts, A. E.; and Rau, W. W., 1958, *Geology and Coal Resources of the Centralia-Chehalis District, Washington*: U.S. Geological Survey Bulletin 1053, 159 p.

Tetra Tech, Inc., 1984, *Final Report–Bellingham Abandoned Mine Land Survey*: Prepared for U.S. Office of Surface Mining, Denver, CO, 36 p.

The Olympian, 1986, Sinkhole back at same old stand: *The Olympian*, Olympia, WA, December 4, 1986, p. 4B.

The Olympian, 1987, Sinkhole closes Seattle streets: *The Olympian*, Olympia, WA, February 16, 1987, p. 2B.

Thorsen, G. W., 1987, Personal communication, Washington Division of Geology and Earth Resources, Olympia, WA.

Walker, C. W. and Shideler, J. C., 1984, *Final Report–Abandoned Coal Mine Hazards in the Roslyn Coal Field, Kittitas County, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 46 p.

Walsh, T. J., 1988, Coal Mine Subsidence in Washington: *Washington Geologic Newsletter*, Vol. 16, No. 3, pp. 3-5.

Watson, J. H., 1887, *Report of the Inspector of Coal Mines and Ventilation of Washington Territory*: By Authority [of the Territorial Printer], Olympia, WA, 27 p.