from several bench marks in the three large-scale project areas were made available to the Bureau as needed by the firm of Johnson-Fermelia & Crank, Inc.

Injection operations at the first test of the pumped-slurry process and at the first large-scale demonstration, both at Rock Springs, were performed by the Dow Chemical Co., Dowell Division, of Tulsa, Okla. A concept that sand slurry could be transported in pipelines directly from the borrow pit to the injection boreholes, a distance of over 2 miles, demonstrated additional flexibility in the use of the pumped-slurry process. Dowell Division personnel who contributed to the success of these nonroutine operations were John D. Stewart, Milton E. Heslep, Robert Hurst, L. D. Boughton, and George Laflin; and also A. J. Meyers on the use of sonar caliper surveys.

Engineers of the WHAN Co. and of the Bober Co., contractors for the second and third large-scale projects, contributed to improving the overall operations through more efficient use of the automated controls of the slurry mixture. In this way, delivery of a more uniform mixture to the injection boreholes was gradually accomplished with a considerable saving in the use of power. As the work progressed they relocated the equipment within the confines of the plant site and altered the use of the equipment from time to time to improve performance and eliminate as much noise and dust as possible.

Charles S. Kuebler, Chief of the Bureau's Environmental Affairs Field Office at Wilkes-Barre, Pa., where similar type projects were being conducted, and E. J. Carlson, engineer, Hydraulics Branch, U.S. Bureau of Reclamation, Denver, Colo., in charge of the model studies, provided valuable insight into the operation of the pumped-slurry method and the behavior of the slurry.

Much of the description of the nature of mine subsidence, its history, and various methods of control, including discussions of the pumped-slurry technique that appear in this report, is attributed to Alice S. Allen and Ralph H. Whaite, authors of Bureau of Mines Information Circular 8667 (22).

BACKGROUND

Development of Rock Springs, Wyo., as a mining community began in the 1860's with the westward extension of the Union Pacific Railroad through southern Wyoming. The railroad's demand for coal persisted well into the 20th century, leaving about 900 acres of Rock Springs undermined. Extraction of coal by the room and pillar method under most of the city had reached an advanced stage, and according to available mine maps it appeared that many of the remaining pillars were too small to support the overburden indefinitely. Under other areas some of the pillars had been removed. Reports of surface subsidence in various parts of the city became noteworthy in the late 1960's. Damage to houses, commercial buildings, streets, gas mains, waterlines, and sewers was considerable.

Subsidence Problems

The city of Rock Springs (fig. 1) is located in Sweetwater County in southwestern Wyoming on U.S. Highway 30, Interstate 80, and the Union Pacific

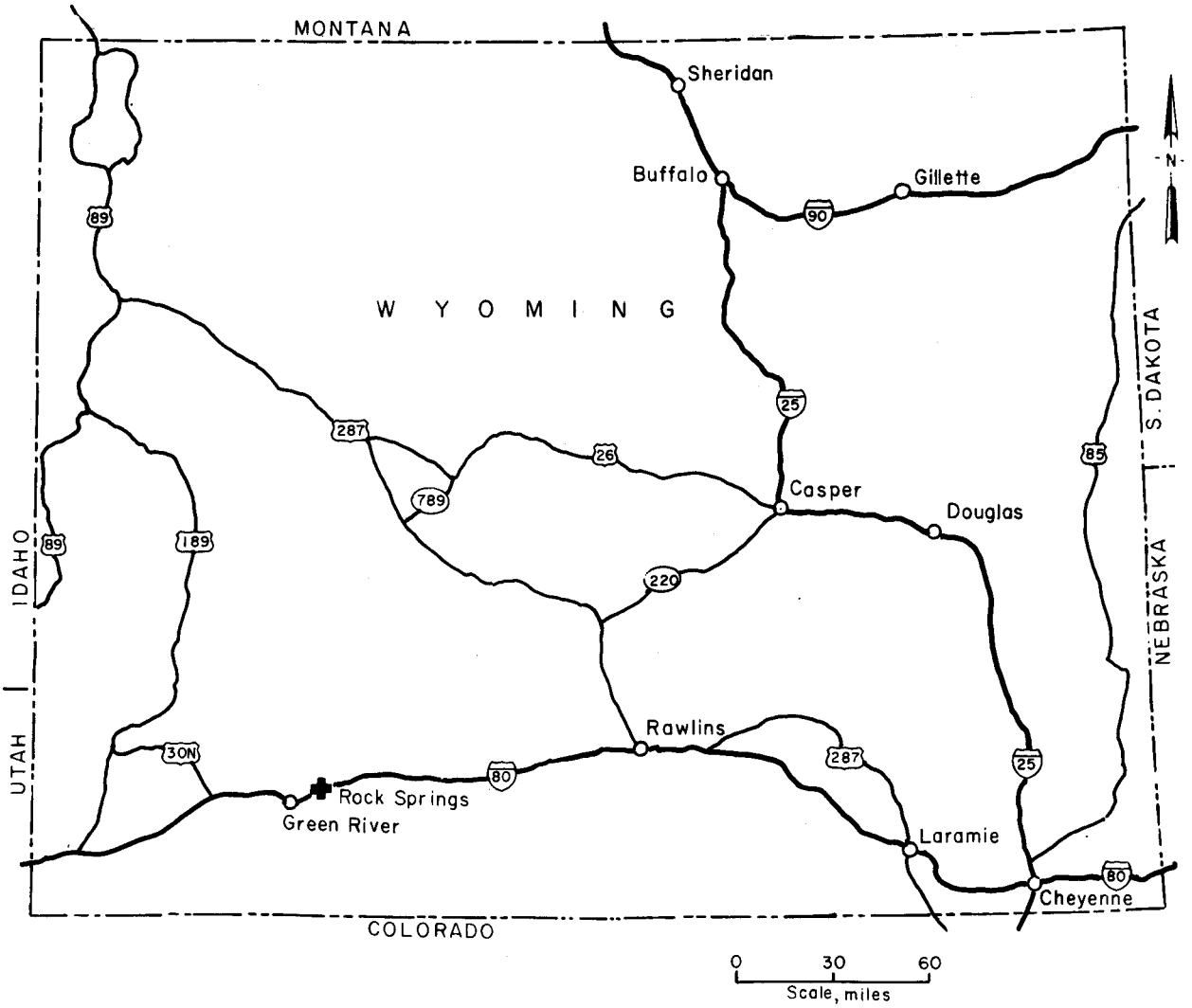

FIGURE 1. - General location map of Rock Springs, Wyo.

Railroad. The 1969 population of the city was about 12,000. Mining of bituminous coal had been the principal industry in the city from the 1860's to the 1950's, and most of the built-up area is extensively undermined, a condition typical of many of the early mining communities. As a consequence, subsidence of the surface, locally termed "sink holes," has plagued Rock Springs for many years. Both the State Highway Department and the Union Pacific Railroad have filled, in some areas, abandoned mine workings beneath their respective rights of way.

In 1969, the Bureau of Mines conducted an investigation of subsidence in Rock Springs, at the request of local authorities, to determine the cause and to recommend solutions (5). Severe subsidence damage had been experienced since 1967 within a 2-acre area in the eastern portion of the city, affecting at least 18 houses and damaging streets, sidewalks, gas mains, waterlines, and sewers. Subsidence was gradual and continuing, achieving maximum

settlement of about 30 inches, accompanied by lateral displacements and some heaving. Elsewhere in the city, localized "potholes" continued to appear on the surface of the ground from time to time.

The site of the severe damage was about 6 blocks from the center of the city near the intersection of Connecticut Avenue and D Street. About one-half of the damage at the time of the investigation was to property known as the Rock Springs Camp owned by the Mountain Fuel Supply Co. The camp consisted of seven dwellings and one office building, all on the north side of D Street. Individual private homes on the south side of D Street were also affected. Ten of the 18 affected houses were seriously damaged.

Subsurface Conditions

From a study of available mine maps it was determined that collapse over mine openings was the principal cause of the subsidence in the Connecticut Avenue-D Street area and in other parts of the city as well. Of the 900 acres of the city that was undermined, Bureau engineers reported that in 15 separate areas ranging in size up to 46 acres, the conditions in the mines with respect to supporting pillars were comparable to those under the Connecticut Avenue-D Street area. These critical areas comprising about 210 acres constituted a significant part of the city, and facilities therein served a wide range of functions. They include sections of the central business district, the city hall, and 828 dwelling units. At the time of the investigation in 1969, it was estimated that the total value of the houses alone was nearly $11 million. Figure 2 is a map of Rock Springs showing the locations of the 15 critical areas.

Geologically, the city of Rock Springs is located on the west edge of the Rock Springs Uplift (10, 20). Bedrock in the area is the Rock Springs Formation of Cretaceous age--an irregular series of coalbeds, carbonaceous shale, siltstone, claystone, and sandstone. The strike of the formations is N 36° E, and the dip is 6° to the northwest at the site of the subsidence. Downdip (northwest of the site) the dip steepens to 30°. Faults are common in the area, but under the built-up section of the city, faulting is believed to be of relatively minor consequence. Figure 3 is a typical cross section of the coal seams under the city of Rock Springs.

Depth to bedrock ranged from 6 to 52 feet in boreholes that were drilled in the Connecticut Avenue-D Street area. The overlying alluvium is silty, very fine sand. A deposit of clay beneath the silty sand was reported in one borehole. The silty sand deposit is of the type that is subject to compaction in the presence of excess water, hence a potential contributor to subsidence. However, in the Rock Springs subsidence area, the evidence indicated that collapse over mine openings was the principal cause of subsidence (13). Deeper strata within the bedrock sequence were found to have been displaced downward, and the pattern of subsidence at street level was observed to reflect the spacing of rooms and pillars in the mine below.

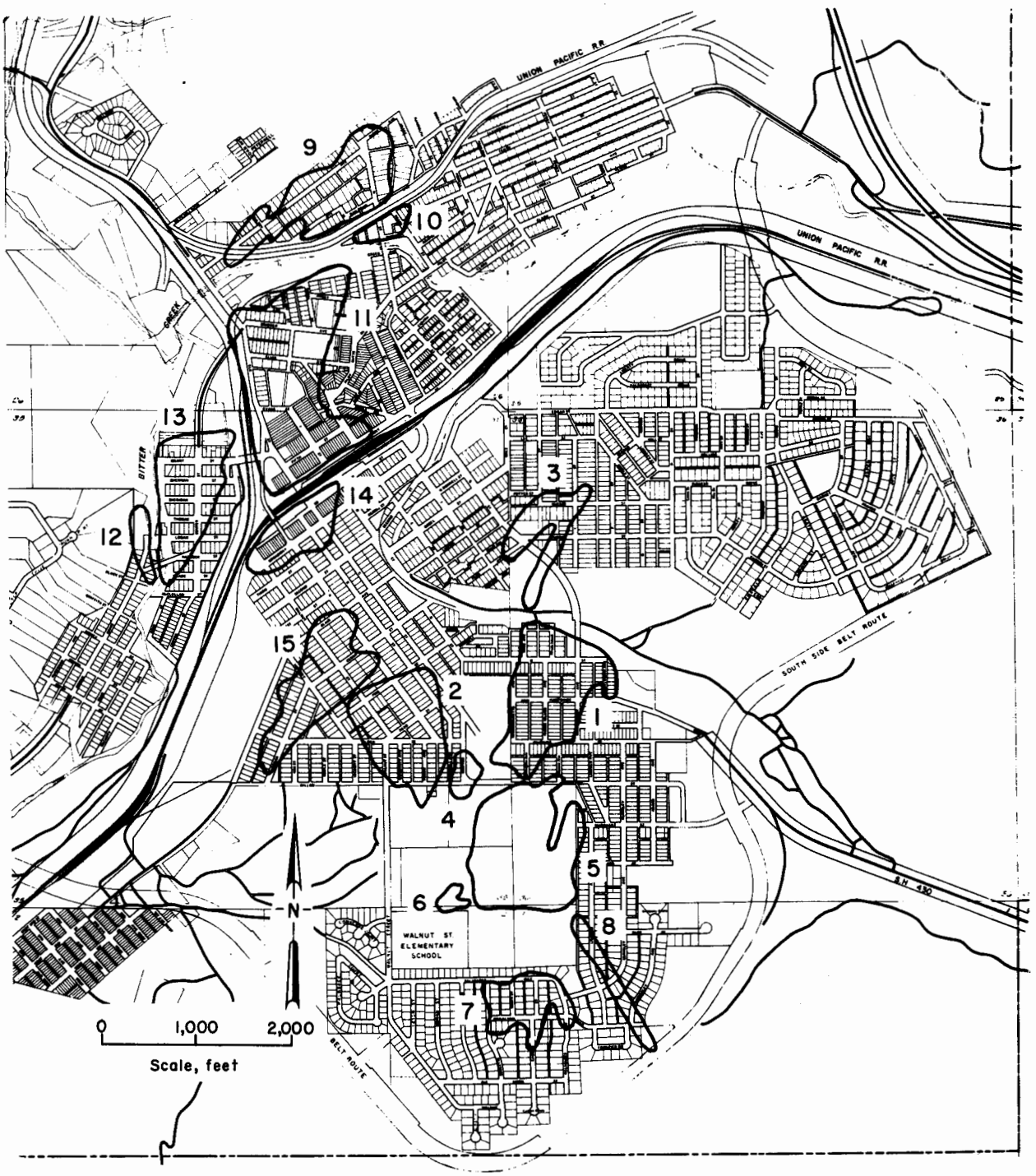

FIGURE 2. - Map of Rock Springs showing the 15 critical areas.

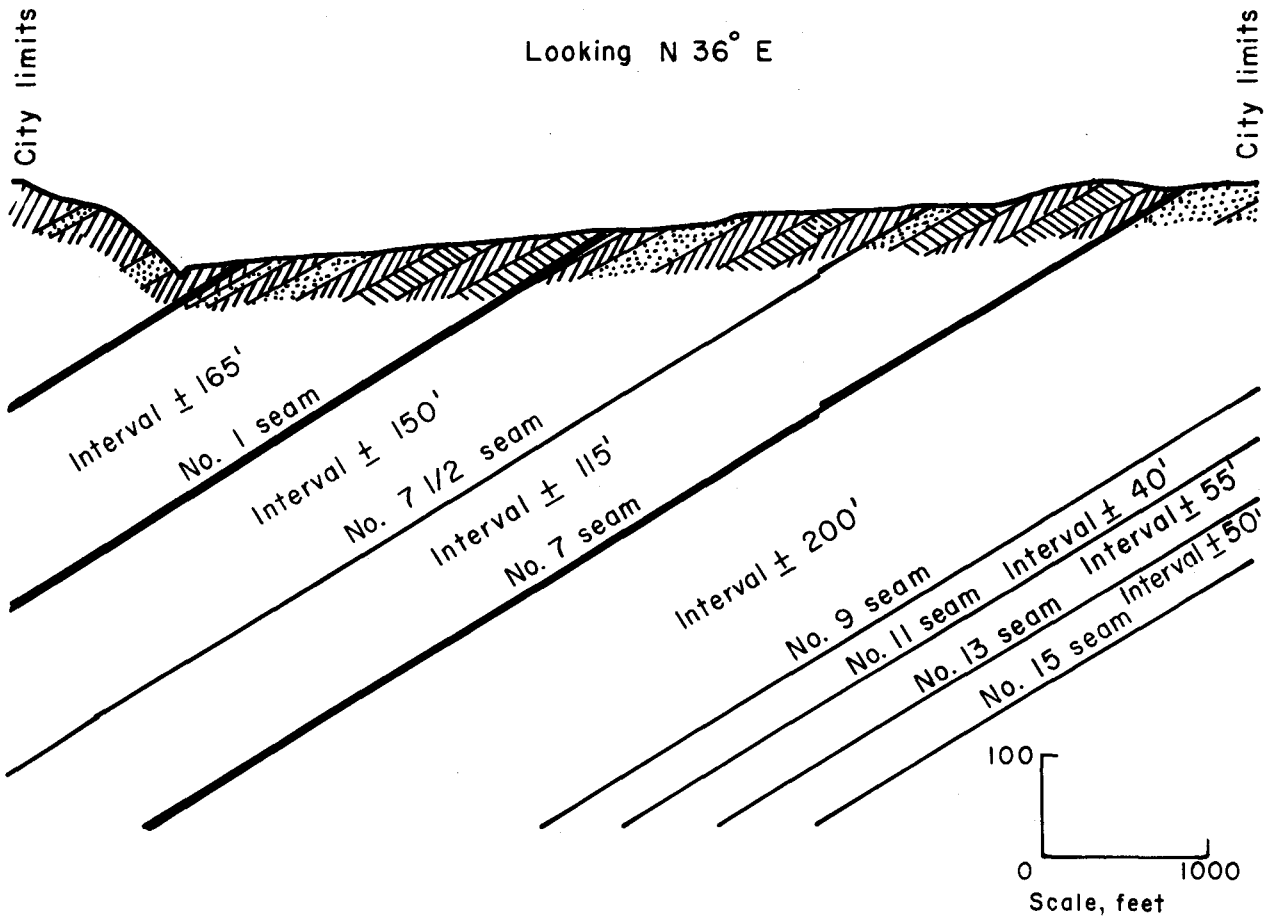

FIGURE 3. - Typical section of the coal seams under the city (note distorted scale; actual dip of seams is 6°).

In the vicinity of Rock Springs, the aggregate thickness of coal exceeds 90 feet. Under the built-up part of the city, two coalbeds were mined extensively, but their structural position is such that one bed has been mined beneath another mined bed in only one section of the city. Two other coalbeds were mined to a lesser degree. The room-and-pillar system of mining was used exclusively. Patterns of extraction, however, were irregular owing to minor faulting and changes in mining techniques over the years.

Water presented a problem during mining operations. Reportedly, one mine pumped 500,000 gallons per day when operating, and water-related problems were a factor in the closing of another mine in the demonstration area. Water levels measured in drill holes indicated that about 75 percent of the workings are now flooded.

A key element in planning successful backfill operations is the availability of accurate and complete mine maps. The information available from mine maps on coalbeds beneath Rock Springs was not complete, and data obtained from drilling indicated that the maps would require adjustment to correlate with surface maps. About a third of the exploratory boreholes, which were drilled to intersect openings according to the maps, terminated in solid pillars of coal.

The Bureau of Mines report included a recommendation that the mine voids in the 15 critical areas, most of which were flooded, should be filled with sand to support remaining pillars, reduce rock strata breakage in the overburden, and minimize possible damage at the surface. To backfill the entire undermined area of the city, about 900 acres, would be difficult and quite expensive because most of the voids, exclusive of the critical areas, are situated at depths in excess of 300 feet below the surface. Based on local observation and experience gained in subsidence control in the Anthracite region, it was assumed that strata breakage originating at depths below 300 feet would not be significant at the surface.

HYDRAULIC BACKFILLING METHODS

Before 1970, two methods of hydraulic placement of backfill material in underground mined-out spaces had been used in the Anthracite region. They are known as controlled flushing and blind flushing. In both methods, granular solid material is sluiced down from the surface through boreholes with water by the force of gravity.

Controlled Flushing

Controlled flushing is possible in mines in which men can safely enter and gain access to key areas for the filling operations. Bulkheads are built in mine passages around the periphery for containment of the fill. Drain boxes may be incorporated in these structures to facilitate rapid removal of water. The injection boreholes, generally about one borehole for 4 acres, are cased from the surface to the mine opening. At the base of each hole, long-radius 90° pipe elbows are placed through which slurry is diverted to horizontal pipes and distributed into the mine workings. Horizontal dispersal ranges from 300 to 1,000 feet, depending on the vertical distance from the ground surface to the mine opening and the solids concentration of the slurry. Controlled flushing provides the best support and is used where conditions permit.

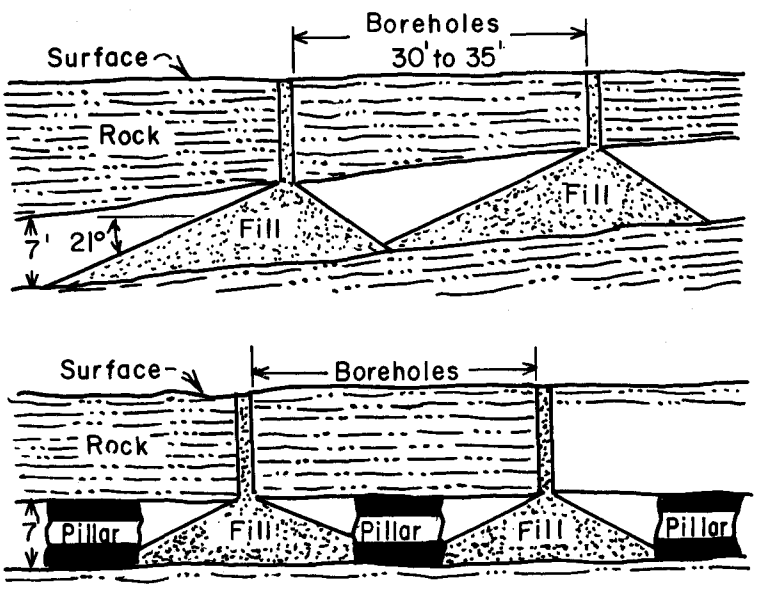

FIGURE 4. - Typical sections showing boreholes and configuration of fill material placed in mine voids by the gravity blind flushing method.

Blind Flushing

Many abandoned mine openings are inaccessible because of flooding or extensive caving. Such openings were flushed blindly in the past. The gravity-feed method simply builds a conical pile beneath the underground opening of the flushing hole. When the apex of the cone builds up to the mine roof, no more fill will enter the mine opening. Further injection must use other boreholes, as shown in figure 4.