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Information Circular 9083

Subsidence Investigations Over Salt-Solution Mines, Hutchinson, KS

By Robert C. Dyni



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CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	2
Acknowledgments.....	2
Geologic setting.....	3
Sinkhole failure mechanisms.....	3
Subsurface investigations.....	5
Cargill 1974 sinkhole (first investigation).....	5
Barton 1952 sinkhole (second investigation).....	7
Carey 1978 sinkholes (third investigation).....	8
Carey well 56 (fourth investigation).....	9
Bureau of Mines surface subsidence investigations.....	12
First and second investigations.....	12
Carey 1978 sinkholes (third investigation).....	12
Background.....	12
Subsidence-monitoring network design and construction.....	12
Monitoring procedures.....	13
Results--vertical movement.....	14
Results--horizontal movement.....	15
Carey well 56 (fourth investigation).....	16
Background.....	16
Subsidence-monitoring network design and construction.....	16
Monitoring procedures.....	16
Results.....	16
Interpretation of results.....	17
First and second investigations.....	17
Third investigation.....	17
Fourth investigation.....	18
Conclusions.....	19
References.....	19
Bibliography.....	20
Appendix A.--Final vertical control survey of Carey brinefield.....	21
Appendix B.--Final horizontal control survey of Carey brinefield.....	22

ILLUSTRATIONS

1. Extent and thickness of Hutchinson Salt Member.....	3
2. Cavity collapse with surface deformations.....	4
3. Location of Cargill and Barton sinkholes.....	5
4. Location of boreholes at Cargill sinkhole.....	5
5. Cross sections of Cargill sinkhole.....	6
6. Location of boreholes at Barton sinkhole.....	7
7. Cross section of Barton sinkhole.....	8
8. Location of Carey sinkholes.....	8
9. Location of boreholes and subsidence monuments at Carey brinefield.....	10
10. Cross section of Carey sinkholes.....	11
11. Cross sections of Carey well 56.....	12
12. Detail of Bureau-designed subsidence monument.....	13
13. Subsidence from R-4 to R-15.....	14
14. Subsidence from R-16 to R-39.....	14
15. Subsidence from R-40 to R-58.....	14

ILLUSTRATIONS--Continued

	<u>Page</u>
16. Subsidence from S-1 to S-12.....	15
17. Subsidence from S-13 to S-21.....	15
18. Subsidence from T-1 to T-12.....	15
19. Subsidence from T-13 to T-20.....	15
20. Horizontal movement of R-4 to R-15.....	16
21. Horizontal movement of S-1 to S-12.....	16

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	yd ³	cubic yard
in	inch	yr	yr
pct	percent		

SUBSIDENCE INVESTIGATIONS OVER SALT-SOLUTION MINES, HUTCHINSON, KS

By Robert C. Dyni¹

ABSTRACT

The Bureau of Mines in cooperation with the Solution Mining Research Institute conducted surface and subsurface investigations over five solution-mined salt cavities in the Hutchinson, KS, area. The purpose of these investigations was to determine the mechanisms that lead to the formation of sinkholes above collapsed solution cavities. Of the five salt-solution cavities investigated, four had collapsed and produced sinkholes prior to the time of the investigations; the fifth cavity was considered stable. Exploratory drilling and coring operations were conducted at all five sites; surface stability monitoring was conducted at three of them. The results of these studies indicate that excessive dissolution at the salt-shale contact of each collapsed cavity produced large, unsupported roof spans that ultimately exceeded the structural integrity of the overburden. The stable cavity was not exposed to excessive dissolution at the salt-shale contact; this limited the roof span and ensured a stable cavity. The data also show that surface settlement in the vicinity of the two surface-monitored sinkholes continued for approximately 7 years after the sinkholes formed, indicating that the rubble piles of the collapsed cavities were undergoing gradual consolidation.

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INTRODUCTION

The Bureau of Mines is actively involved in making mineral production compatible with the environment. The formation of sinkholes due to the structural failure of solution-mined cavities in salt is a potentially hazardous event that can threaten lives and damage or destroy structures and property. The Bureau, in cooperation with the Solution Mining Research Institute (SMRI), conducted a series of four investigations designed to provide an understanding of the physical parameters and mechanisms involved in sinkhole formation. The results of this research will assist in establishing a basis for sound salt-solution cavity design that will prevent cavity collapse and sinkhole formation.

Extensive research has been performed by SMRI and others in an attempt to understand the geologic parameters associated with sinkhole formation, but little work has been done to correlate solution-cavity deformations to ground surface movements.² Therefore, the primary methodologies of the four investigations conducted by the Bureau and SMRI were designed to correlate these two parameters.

The study sites chosen for the four investigations were located over salt-solution mining operations in the Hutchinson, KS, area. In 1977 the Bureau and SMRI conducted the first investigation at a sinkhole that had formed on the property of Cargill Salt in October 1974. This investigation consisted of a drilling and coring program designed to determine the shape of the underlying solution cavity, to evaluate the composition and condition of the overburden, and to determine the mechanisms that led to the formation of the sinkhole. The Bureau

was responsible for contracting the drilling and coring operations; SMRI contracted for the analyses of the data and preparation of the report of the investigation.

In 1978 the second investigation was carried out at a sinkhole that had formed in June 1952 on the property of the Barton Salt Co., now owned by Cargill Salt. As in the previous investigation, a Bureau-contracted drilling and coring program was conducted, and the data were analyzed and a report of the investigation was prepared under contract to SMRI.

The third investigation was performed in 1979 in the vicinity of two sinkholes that had formed in 1978 at the Carey Salt brinefield. The Bureau again funded a drilling and coring program, and an SMRI contractor analyzed the data and prepared a report of the investigation. The Bureau also installed and monitored a surface survey network designed to detect any ground surface movements associated with the two cavity failures.

The fourth investigation was also carried out at the Carey brinefield in 1981-82. This investigation differed from the other three in that it was conducted at a brine cavity that had not experienced any apparent ground movements and yet had a mining history similar to those of the neighboring cavities that had failed. The subsidence-monitoring network installed for the previous investigation was extended to accommodate monitoring of the area over the stable cavity. Another Bureau-contracted drilling and coring program was conducted, and the data analysis and report preparation were again done under contract to SMRI.

ACKNOWLEDGMENTS

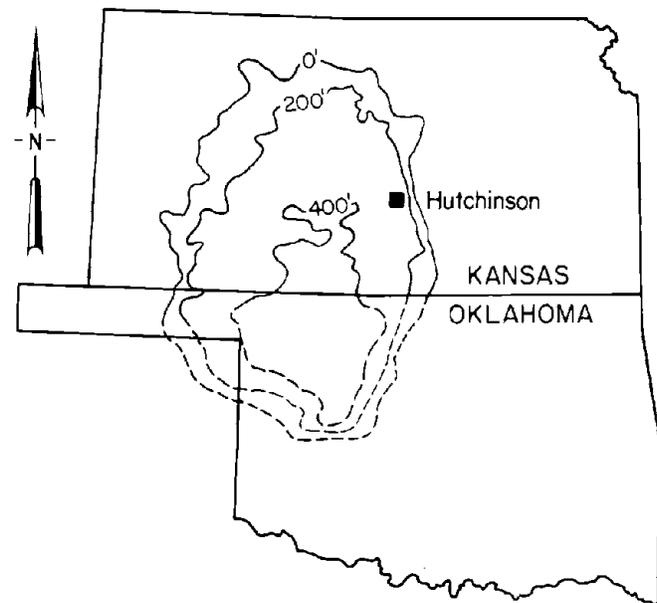
The personnel at the Cargill Salt Co. and the Carey Salt Division of Processed Minerals, Inc., Hutchinson, KS,

provided valuable assistance in conducting this research. In particular, Larry Schulte, vice president and director of manufacturing, Carey Salt, made significant contributions to the project by providing access to company property and company mining records.

²The bibliography preceding the appendixes at the end of this report lists relevant previous research on sinkhole formation.

GEOLOGIC SETTING

The Hutchinson Salt Member of the Permian Wellington Formation underlies a large area of central and south-central Kansas and north-central Oklahoma. Figure 1 depicts the extent and thickness of the Hutchinson Salt Member. The zero thickness line in figure 1 indicates a depositional edge to the west, northwest, north, and northeast. The southwest edge of the salt undergoes a facies change to anhydrite and dolomite, and the east edge is erosional. The salt bed in the Hutchinson area is approximately 400 ft beneath the surface and has a thickness of about 325 ft. It consists of bedded halite with interbeds of shale. Overlying the salt is an aquitard comprised of 350 ft of Permian shales and siltstones. The surface deposits that overlie the aquitard are aquifers comprised of unconsolidated sand and gravel beds with a combined thickness of about 45 ft (6, pp. 5-10; 7, p. 12).³ A complete description of the regional geology of the Hutchinson area is given by Walters (6, pp. 5-26).



LEGEND

- 200'— Thickness of salt deposit in ft
 - - - - - Facies change

FIGURE 1.—Extent and thickness of Hutchinson Salt Member.

SINKHOLE FAILURE MECHANISMS

According to Hendron (4, pp. 2-13), rapid sinkhole development above solution-mined cavities in bedded salt formations as found in the Kansas region requires four conditions:

1. The presence of a large unsupported roof span at the salt-shale contact.
2. A large-volume cavity beneath the unsupported shale roof.
3. Triggering mechanisms.
4. In situ conditions that preclude arch formation in the shale roof.

Large, unsupported roof spans in solution cavities can be created in various ways. The solution mining of salt through single boreholes with casing

set in the shales above the salt and tubing extending into the deposit can develop cavities that expose the roof rock to the deteriorating action of fresh water or undersaturated brine. The practice of reverse circulation also leads to this condition. Once these layers are exposed and come in contact with fresh water or brine, they disintegrate and lose most of their shear strength and arching capacity. When roof rock falls from the roof of a solution cavity, the resulting rubble pile propagates toward the top of the cavity, and at the same time the roof becomes progressively higher. The distance from the top of the cavity to the top of the rubble pile decreases during this process because of the bulking of the rubble. If the distance between the top of the cavity and the top of the rubble pile becomes zero before the top of the cavity reaches the

³Underlined numbers in parentheses refer to items in the list of references preceding the bibliography and appendixes.

upper shale surface, then the roof will start receiving support by the rubble and the bulking process will be stopped (fig. 2A). A shallow sinkhole may develop as a result of the downward deflection of the shale roof and the consolidation of the rubble pile even though the bulking process has been halted (fig. 2B). If, however, the distance between the top of the cavity and the top of the rubble pile does not become zero before the roof reaches the upper shale layers, then a chimney forms and propagates through the upper shale layers to the unconsolidated soils near the surface. This material then flows down into the remaining void and can create a deep sinkhole (fig. 2C).

A trigger mechanism that reduces critical support from a marginally stable roof can consist of a reduction of brine pressure inside the cavity, a reduction of the buoyancy effect on shale fragments suspended from the roof of the cavity, or the removal of critical roof support by continuing salt dissolution. Hendron (4) indicates that these conditions most

likely are interrelated and act simultaneously to initiate the failure of a cavity roof.

If all four conditions for rapid sinkhole development are met, a deep sinkhole as shown in figure 2C will most likely be the result. If, however, only a large unsupported roof span at the salt-shale contact and triggering mechanisms are present, shallow sinkholes as shown in figure 2B can possibly form. Shallow sinkholes do not develop as rapidly as deep sinkholes, and their dimensions may increase with time. As mentioned earlier, the bulking process in shallow sinkholes does not progress up to the ground surface, and no chimney is formed in the shale layers. If only the first condition is met, the unsupported shale layers above the cavity will tend to deflect down into the opening, producing subsidence on the ground surface. This subsidence develops gradually over a long period and affects a large surface area over the cavity (4, pp. 3-4). Further analysis on sinkhole failure mechanisms is provided by Hendron (4).

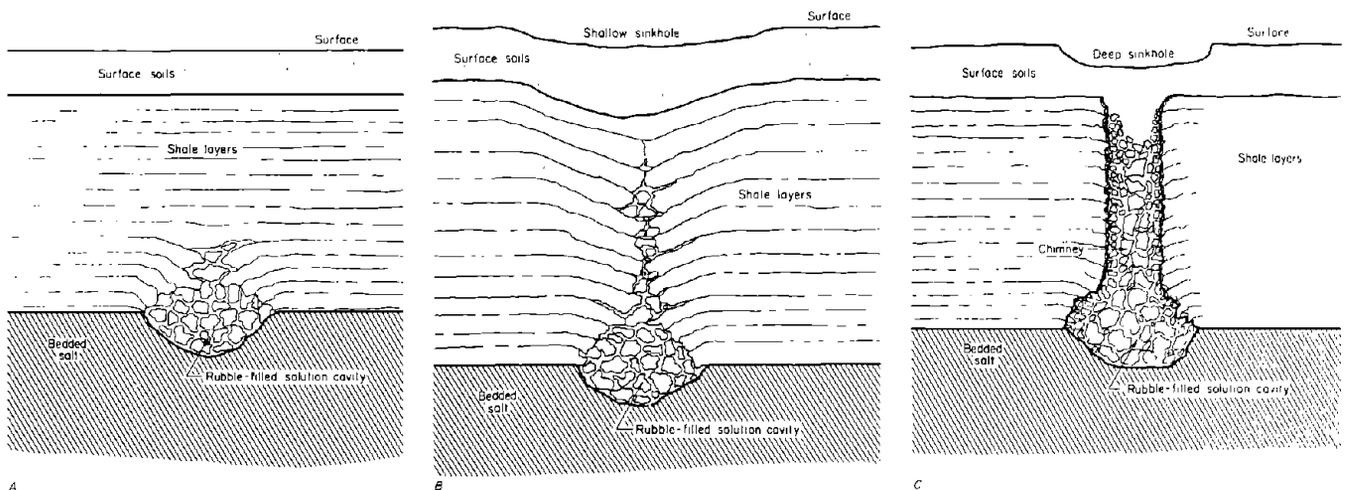


FIGURE 2.—Cavity collapse with surface deformations.

SUBSURFACE INVESTIGATIONS

The purpose of the subsurface investigations was to provide information on the conditions of the four brine cavities. By using drilling and coring procedures, information on overburden composition and conditions and on general solution cavity dimensions was obtained for each brine cavity.

CARGILL 1974 SINKHOLE
(FIRST INVESTIGATION)

The site of the first cooperative investigation performed by SMRI and the Bureau was a sinkhole that had formed

south of the Cargill salt plant in October 1974 (fig. 3). At the time of the investigation, the sinkhole had an approximate surface diameter of 300 ft and a maximum depth of about 60 ft.

The investigation consisted of drilling four vertical (V-1 to V-4) and two 30° inclined (I-1 and I-2) exploratory borings in the vicinity of the sinkhole (fig. 4). The borings were drilled along two perpendicular lines that intersected at the approximate center of the sinkhole. Three of the six borings, V-1, V-2, and I-1, were drilled on the northeast-southwest line; this line coincided with the alignment of a series of brine wells in the area. The other three borings, V-3, V-4, and I-2, were drilled on the northwest-southeast line. The vertical boreholes ranged in depth from 268 ft in boring V-2 to 525 ft in

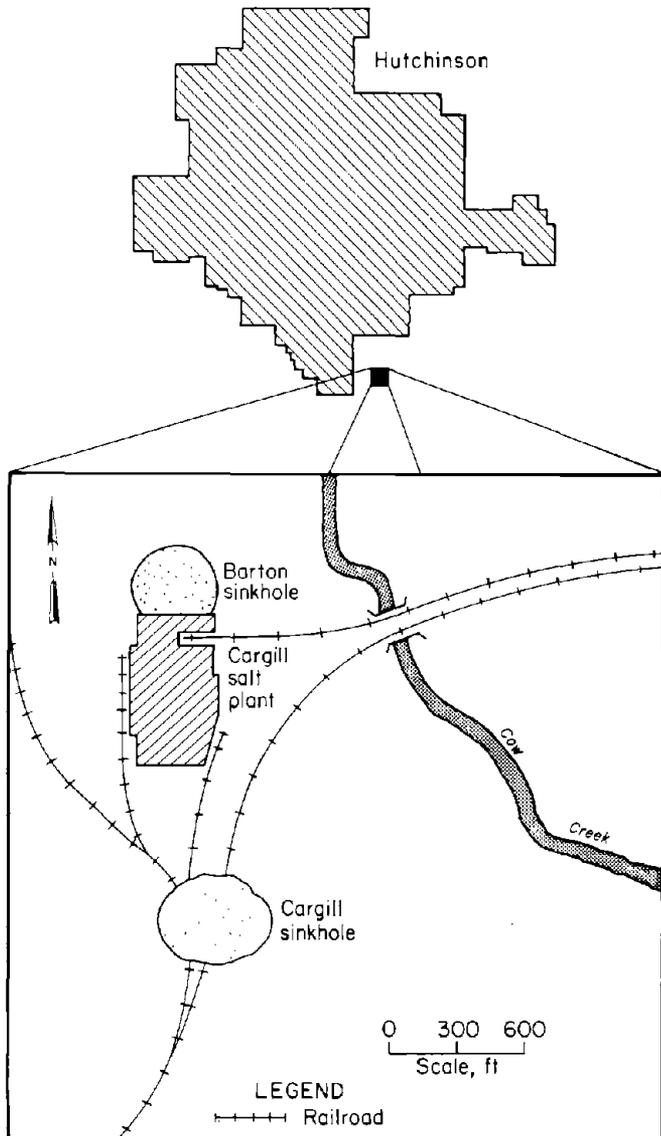


FIGURE 3.—Location of Cargill and Barton sinkholes.

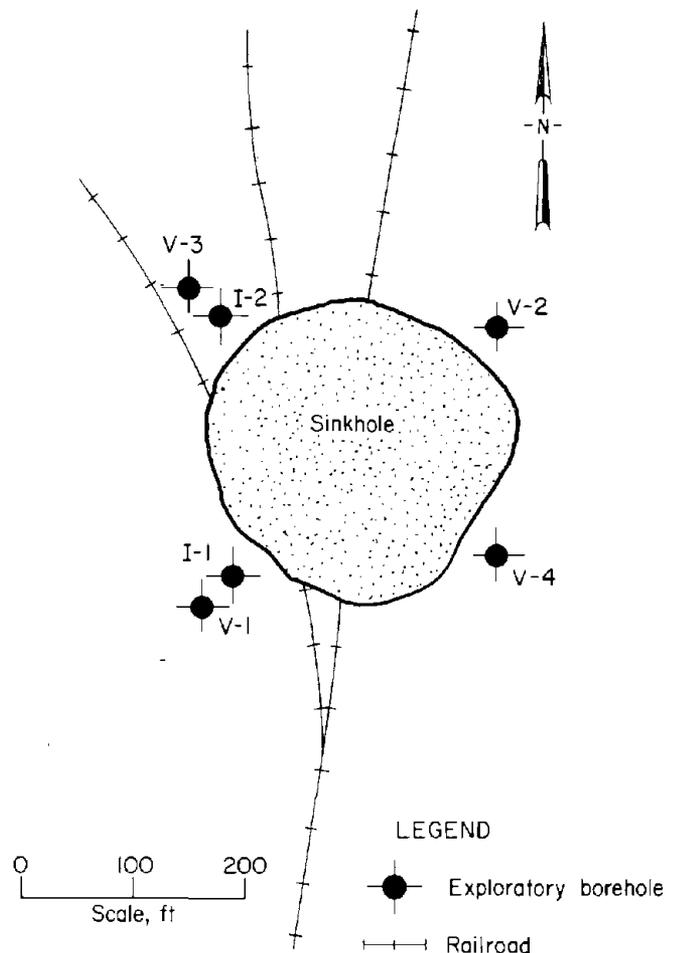


FIGURE 4.—Location of boreholes at Cargill sinkhole.

boring V-3. The inclined boreholes I-1 and I-2 were each about 260 ft in depth. Complete details on the drilling and coring procedures are given by Hendron (1, pp. 1-2).

Borings V-3 and V-4 each encountered the top of the salt deposit at a depth of approximately 420 ft. These borings found no evidence of any surface sands from the sinkhole, or any voids or disturbances in the strata overlying the salt. Borings V-1 and V-2, however, both found evidence of voids and disturbances in the shale at depths of approximately 240 to 245 ft, and boring V-1 also found a large void and surface sands from the sinkhole at a depth of about 388 ft. These findings indicate that an elongated cavity had developed in the northeast-southwest direction under the sinkhole, caused by the solution activity of the neighboring brine wells. The evidence also suggests that the roof shale over

the salt had caved upward about 30 ft at the location of boring V-1, and that some large block movements of the shale had extended as much as 180 ft into the shale above the elongated cavity (1, pp. 7-8). Walters (6, p. 45) suggests that the configuration of the elongated cavity exceeded the span capabilities of the overlying rock layers. This allowed the failure of these layers to breach the uppermost shale layer and permit approximately 90,000 yd³ of sand and gravel to move down into the opening (2, p. 2). The sand that was encountered in the inclined borings I-1 and I-2 indicates that an approximately 100-ft-diam chimney of sand was located below the center of the sinkhole. The sinkhole and the chimney both were elongated in the northeast-southwest direction, indicating that the influence of the underlying cavity elongated along the line of brine wells in the area (1, p. 8). Figure 5 shows

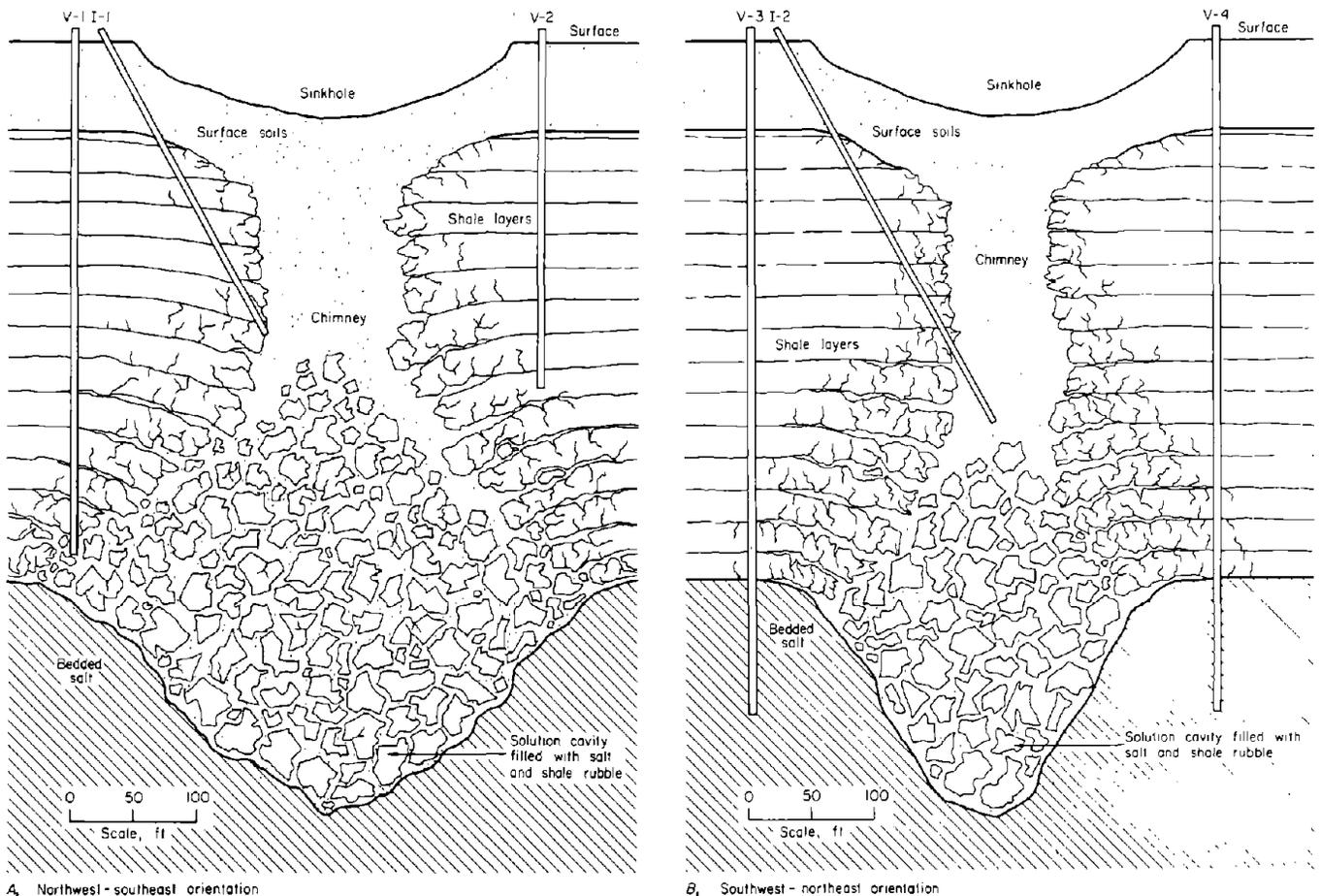


FIGURE 5.—Cross sections of Cargill sinkhole.

cross-sectional representations of the sinkhole. Details of the drilling results and the conclusions drawn from these results are given in a report by Hendron (1). An analysis on the causes, mechanisms, and time framework of the sinkhole is given by Walters (6, pp. 32-39, 45-46).

BARTON 1952 SINKHOLE
(SECOND INVESTIGATION)

The second investigation took place in 1978 in the vicinity of a sinkhole that formed in June 1952 on the property of the Barton Salt Co., now owned by Cargill Salt (fig. 3). The sinkhole had formed in the vicinity of an old brine well which was believed to have been drilled in the late 19th or early 20th century by the G & H Salt Co. The sinkhole had a surface diameter of about 250 ft and a maximum depth of about 30 ft, and was backfilled shortly after it formed. The sinkhole now lies beneath a parking area and a section of the Cargill plant and continues to undergo differential settlements (3, p.1; 6, p. 29).

The investigation consisted of drilling six shallow (S-1 to S-6) and five deep (V-1 to V-5) exploratory borings in the vicinity of the sinkhole (fig. 6). The six shallow borings extended through the unconsolidated surface soils to the upper shale surface, and the five deep borings extended to various depths in the shale. The purpose of the shallow borings was to determine the limits of the subsidence area by defining the depression in the upper shale surface, and to determine the locations for the deep borings. Details on the drilling and coring procedures are given by Hendron (3, pp. 3-5).

The salt deposit was encountered at a depth of 497 ft in boring V-1, 435 ft in boring V-3, and 423 ft in boring V-5 (fig. 7). Boring V-1 encountered intact, but disturbed, shale down to a depth of 442 ft; the remaining 55 ft consisted of shale and salt roof-fall rubble which filled the solution cavity. Boring V-3 encountered intact, but disturbed, shale down to a depth of 425 ft; the remaining 10 ft consisted of shale and salt

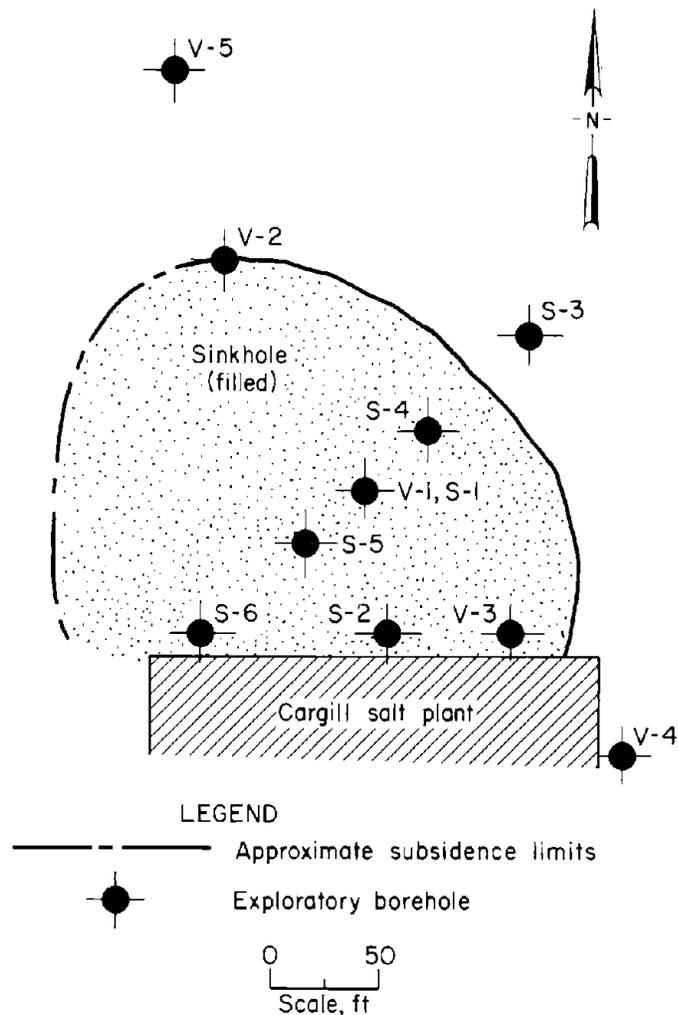


FIGURE 6.—Location of boreholes at Barton sinkhole.

roof rubble. Boring V-5 did not encounter any disturbed shale or roof-fall material, and thus was considered to be located outside the affected area. Boring V-2 terminated at 260 ft and boring V-4 terminated at 406 ft, both because of difficulties encountered while drilling. The results from the shallow borings indicate that the upper shale surface experienced a downward deflection in an area centered around boring V-1. The maximum deflection of the upper shale surface was measured to be approximately 25 ft at boring V-1, and the entire affected area had a diameter of approximately 240 ft. Based on the results of the deep and shallow borings and gamma-neutron logs, Hendron suggests that the subsidence over the solution cavity was

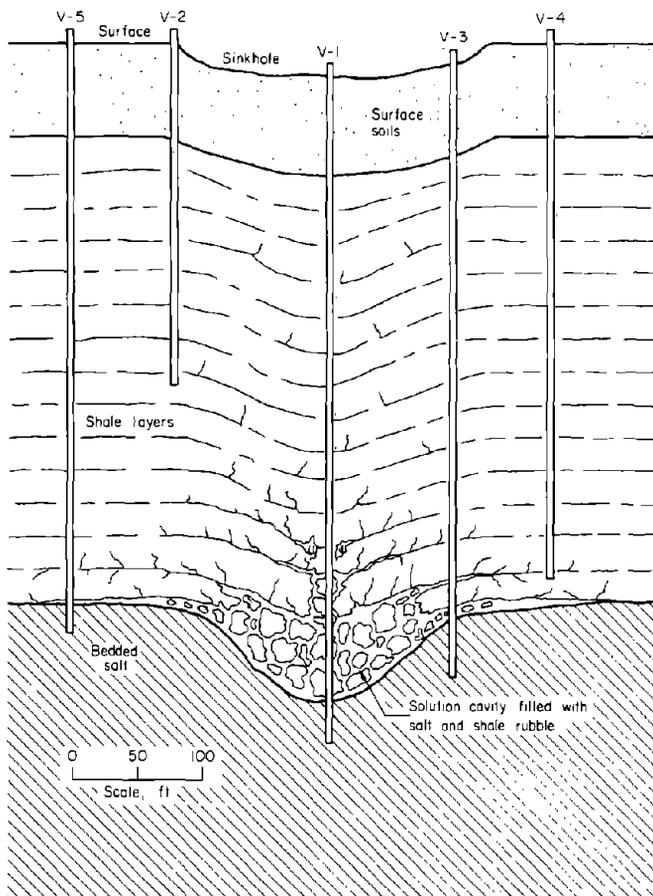


FIGURE 7.—Cross section of Barton sinkhole.

due to deterioration, tensile cracking, stoping, and downward movement of the basically intact shale mass. From the results of the deep borings, Hendron infers that no salt remained in the cavity roof at the location of boring V-1 and that approximately 20 ft of shale had stoped from the top of the cavity. The deterioration of the roof ultimately led to the loss of the ability of the roof to span the cavity by arching, causing the roof to break and sag and come to rest on the rubble pile that filled the cavity (3, pp. 26-31).

CAREY 1978 SINKHOLES (THIRD INVESTIGATION)

The third investigation, jointly performed by SMRI and the Bureau, took place in 1979 at two sinkholes that formed in

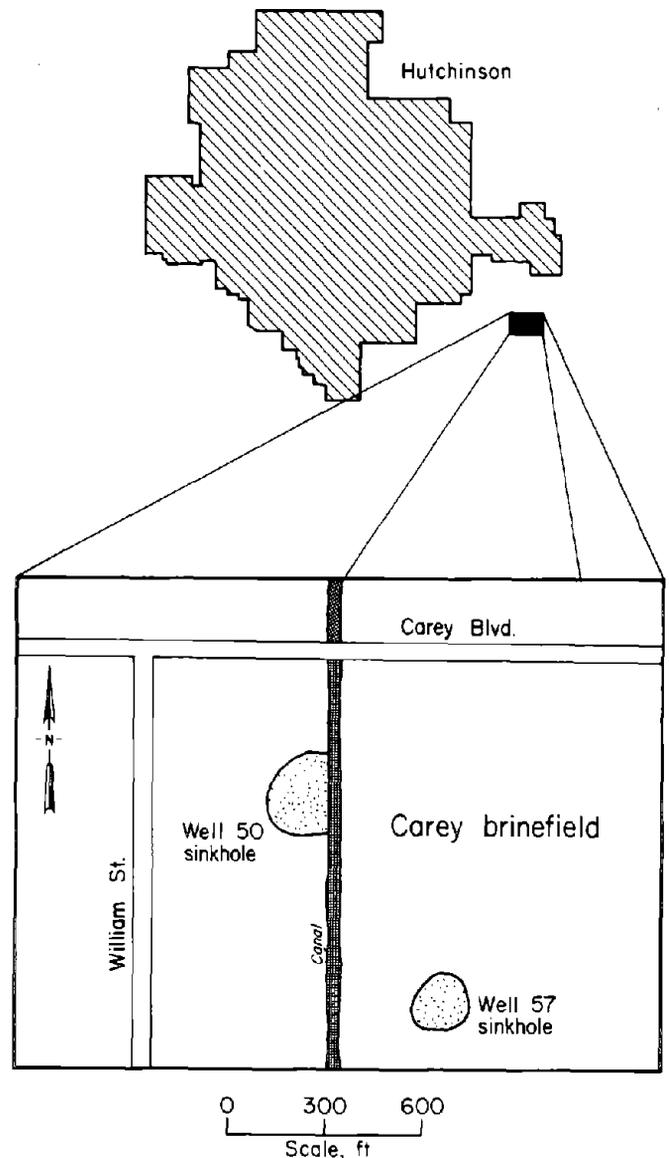


FIGURE 8.—Location of Carey sinkholes.

1978 around two wells at the Carey Salt brinefield (fig. 8). The two wells, well 50 and well 57, were both part of an interconnected nine-well gallery. The area around well 57 began subsiding on May 31, 1978, and continued to settle through June 2. The resulting depression was approximately 120 ft in diameter and had a depth of about 10 ft. The area around well 50 began to subside on June 7, a week after the first movements around well 57 were observed, and continued to subside for several days, leaving a

depression approximately 260 ft in diameter and 13 ft in depth (7, p. 8). Details on production practices for the wells operating in the area at the time of the sinkhole formations are given by Walters (7, pp. 6, 13-15).

The investigation consisted of exploratory drilling and coring around the subsidence areas, and installing and monitoring a subsidence-monitoring network on the ground surface. The Bureau installed and monitored the network, while SMRI was responsible for supervising the Bureau-contracted drilling and coring operations. Details on the monitoring network are given in the "Bureau of Mines Surface Subsidence Investigations" section.

Five vertical borings (V-1 to V-5) and one inclined boring (I-1) were drilled in the vicinity of the two subsidence areas (fig. 9). Borings V-1 to V-4 were designed to determine the subsurface conditions beneath the depression around well 57; boring V-5 was designed to delineate gallery development between the two subsidence areas; and boring I-1 was designed to determine the subsurface conditions beneath the depression around well 50. Boring V-1 was advanced to a depth of 456 ft, boring V-2 to 495 ft, boring V-3 to 455 ft, boring V-4 to 431 ft, and boring V-5 to 451 ft. The inclined boring I-1 was advanced to 347 ft (5, pp. 7-10). Details on the drilling and coring procedures are given by Hendron (5, pp. 7-10).

The drilling and coring results indicated that a large, unsupported roof span existed above the well 57 solution cavity (fig. 10). Borings V-1, V-3, and V-4 each found evidence of a thin, rubble-filled cavity. Boring V-2, located near the center of the depression area around well 57, indicated that this same cavity had a much larger vertical extent in this area. The materials recovered from borings V-1 and V-3 included intact undisturbed shale, sagged

and disturbed shale, roof-fall rubble, and undisturbed salt beneath the rubble. Borings V-2 and V-4 recovered sagged and disturbed shale, roof-fall rubble, insolubles and fallen stringers (V-2 only), and undisturbed salt beneath the rubble. None of the borings drilled near well 57 found any evidence of salt in contact with the shale that had formed the cavity roof; thus, it was inferred that no salt remained in the roof of the cavity prior to its collapse (5, pp. 31-40). Hendron suggests that the formation of the two subsidence areas around wells 50 and 57 was due to the development of large roof spans in the solution cavities where the shale had been exposed, softened, and cracked during well operation. The combination of these factors induced roof collapse as well as excessive sagging of the shale above the roof. Complete failure of the overlying shale did not occur because the rubble that had stopped from the roofs of the cavities provided support on which the shale came to rest. It is possible that a hydraulic connection developed between wells 50 and 57, inducing the collapse of the overlying shale (5, pp. 40-42). Details on the analysis of the drilling and coring results are given by Hendron (5, pp. 31-42).

CAREY WELL 56 (FOURTH INVESTIGATION)

The fourth investigation took place in 1982 in the vicinity of well 56 located at the Carey brinefield. Well 56 is located in the same gallery that contains the failed cavities of wells 50 and 57 (fig. 9). Although the area around well 56 had not experienced any measurable ground surface movements, the stability of the solution cavity was unknown. Surface monitoring would either confirm its continued stability or detect any possible movements. The exploratory drilling program would determine whether or not the solution cavity was stable, if

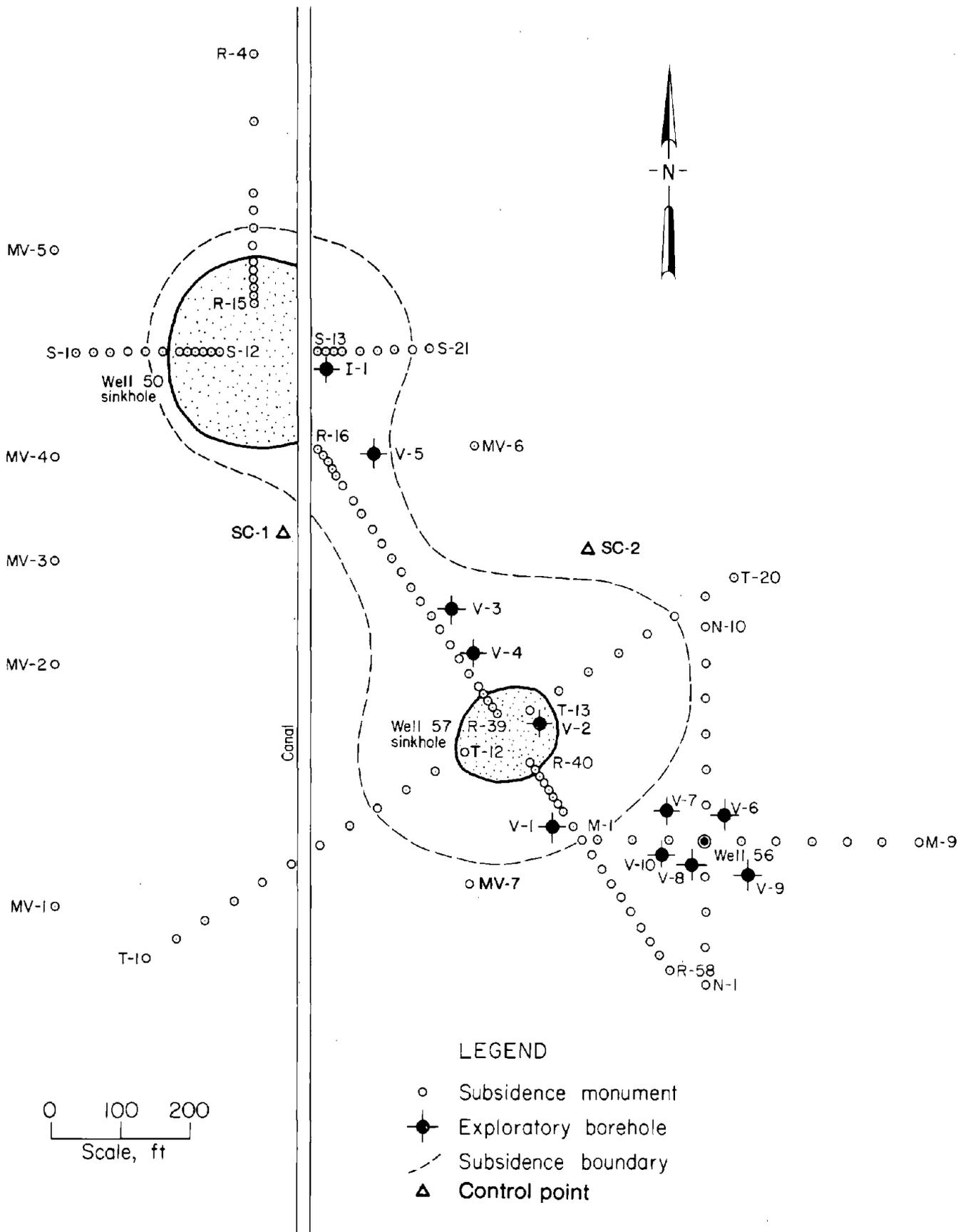


FIGURE 9.—Location of boreholes and subsidence monuments at Carey brinefield.

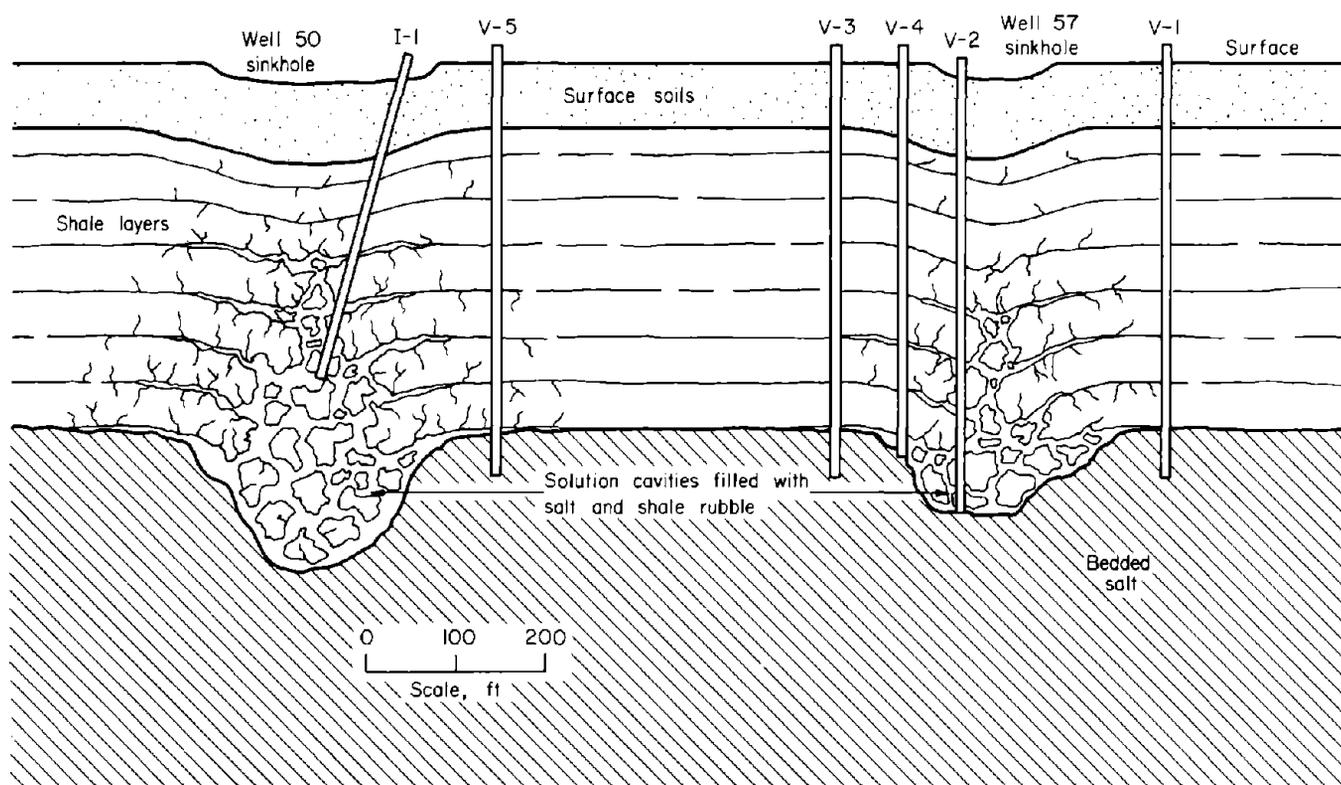


FIGURE 10.—Cross section of Carey sinkholes.

the cavity was in some stage of progressive failure, or if the cavity was presently stable but likely to fail in the future.

The investigation consisted of drilling and coring five (V-6 to V-10) exploratory borings and extending the subsidence-monitoring network to the area around well 56 (fig. 9). The Bureau was responsible for extending and monitoring the network, and SMRI was responsible for supervising the drilling and coring operations funded by the Bureau. Boring V-6 was advanced to a depth of 565 ft, boring V-7 to 436.5 ft, boring V-8 to 515 ft, boring V-9 to 502.5 ft, and boring V-10 to 552.5 ft (2, pp. 8-9). Details on the drilling and coring procedures are given by Hendron (2, pp. 8-9).

The drilling and coring results indicated the shale overlying the solution cavity was intact and undisturbed to within several feet of the salt-shale contact (fig. 11). Near the roof, the shale had softened and undergone

bed separations. The cavity appeared to be elongated in the southeast-northwest direction with a roof span of about 150 ft. In the southwest-northeast direction, the roof span was estimated to be approximately 50 ft. The restricted roof span dimensions near the shale were most likely due to the fact that well 56 had been operated by pumping fresh water down the tubing that extended close to the bottom of the salt deposit. This resulted in most of the solutioning occurring deep in the salt and away from the overlying shale. The borings also indicated that there was only a limited amount of shale exposed in the roof of the cavity that was subjected to deterioration by fresh water (2, pp. 37-39). Hendron (2, p. 39) suggests that the limited exposure of the shale to the deteriorating action of fresh water beneath the well in combination with the limited roof spans over the cavity led to a stronger roof support and a stable cavity.

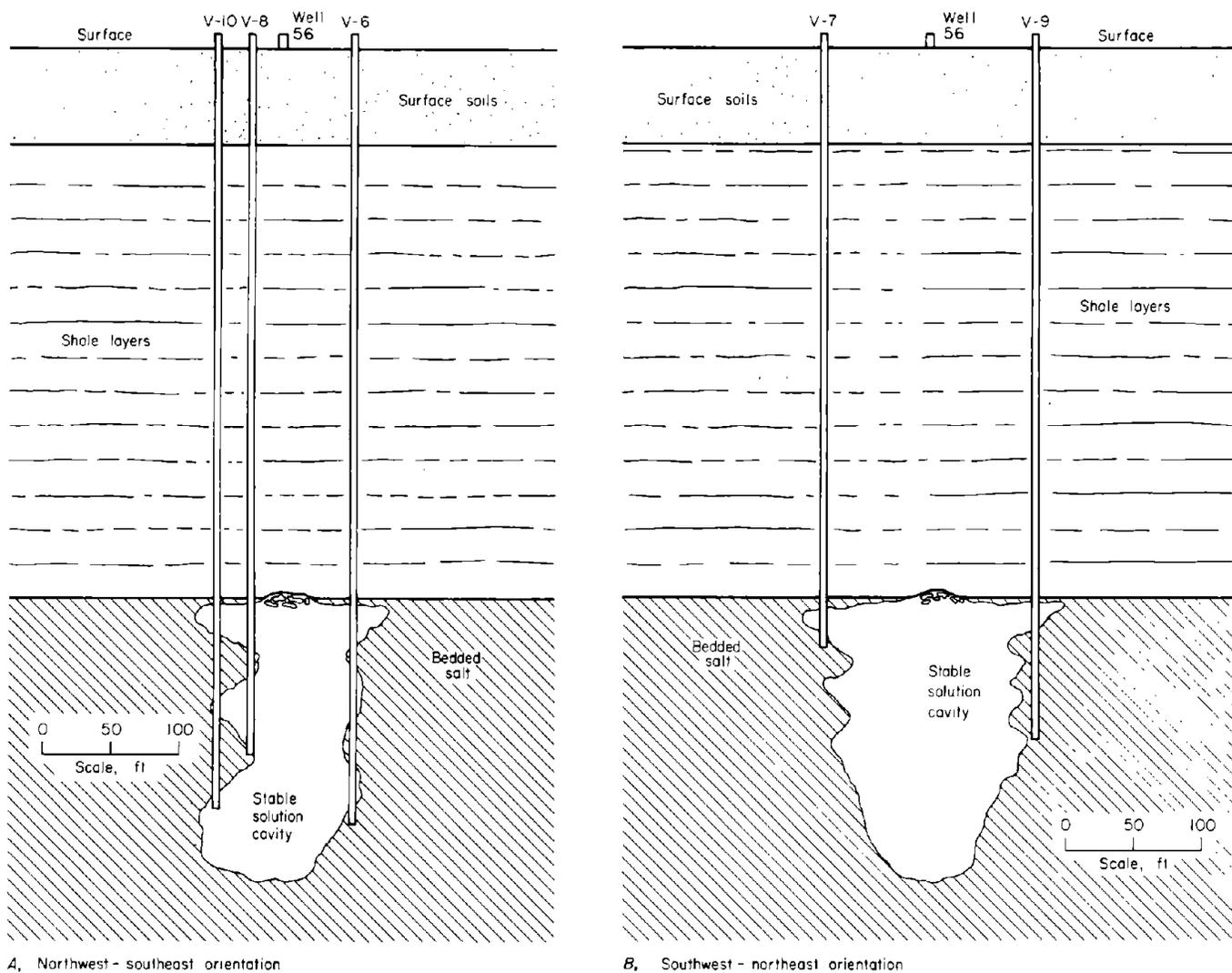


FIGURE 11.—Cross section of Carey well 56.

BUREAU OF MINES SURFACE SUBSIDENCE INVESTIGATIONS

FIRST AND SECOND INVESTIGATIONS

The investigations carried out at the Barton and Cargill sinkholes did not include surface monitoring programs.

CAREY 1978 SINKHOLES
(THIRD INVESTIGATION)

Background

In 1979 the Bureau installed a subsidence-monitoring network around wells 50 and 57 in the Carey brinefield. A total of 154 survey points were used to monitor the horizontal and vertical ground surface movements in the vicinity of the

two sinkholes. The network consisted of 1 existing control point, 4 Bureau-installed control points, 103 Bureau-installed subsidence monuments, 10 Carey-installed subsidence monuments, and survey marks set on the 6 exploratory borings and on 30 brine wells.

Subsidence-Monitoring Network Design and Construction

The network (fig. 9) was designed to monitor any positional changes of the ground surface associated with the two sinkholes around wells 50 and 57, as well as in other areas of the brinefield. The S-line (S-1 to S-21) and a portion of the

R-line (R-4 to R-15) subsidence monuments were positioned in the area around the well 50 sinkhole. These two monument lines intersected at right angles near the center of the well 50 sinkhole. The T-line (T-1 to T-20) and the remainder of the R-line (R-16 to R-58) monuments were positioned in the area around the well 57 sinkhole. These two monument lines intersected at right angles near the center of the well 57 sinkhole. The monuments R-16 to R-58 were also designed to monitor the area between the two sinkholes and were therefore oriented along the axis between the two sinkhole centers. The MV-line monuments were distributed throughout the area around the sinkholes to monitor any ground surface movements due to neighboring wells. The remainder of the survey points, including the wells, boreholes, and previously installed survey movements, were used to monitor movements of the ground surface over a large area around the two sinkholes. Control points P-1, P-2, and P-3 were placed in areas that were considered to be stable and not affected by solution mining activities; these control points were located in areas outside the area shown in figure 9. Control points SC-1 and SC-2 were located in the brinefield for the trilateration surveys and were checked for stability prior to each survey.

The 4 control points and the 103 monuments installed by the Bureau at the Carey brinefield were all of the same design and construction (fig. 12). The monument consists of a small inner pipe fitted with a pointed anchor on the bottom and a reference-marked cap on the top, and a large outer pipe which is used to drive the anchor below frost depth. The inner pipe extends through a cap on top of the outer pipe. The outer pipe is free to undergo movements due to frost heave or swelling and shrinking soils without affecting the inner pipe on which measurements are made. The monuments proved to be very stable and effectively guarded against soil distances throughout the entire time of the investigation.

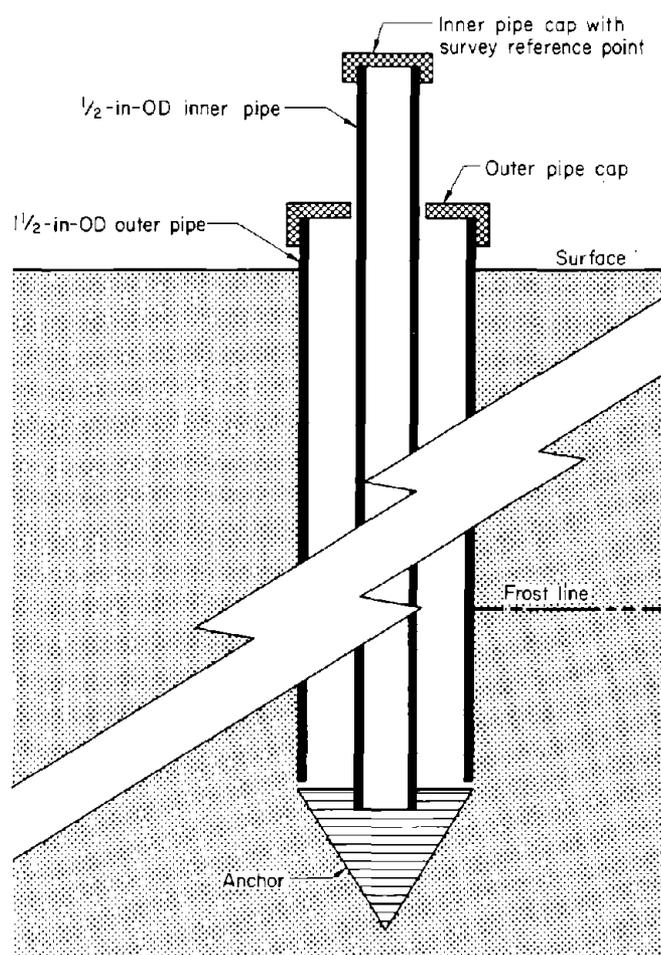


FIGURE 12.—Detail of Bureau-designed subsidence monument.

The wells, boreholes, and structures that were used as subsidence monuments all had survey marks that provided consistent reference points.

Monitoring Procedures

The procedures used to monitor positional changes in the network involved various survey techniques. Trilateration and traverse surveying procedures were used for horizontal control, and trigonometric and differential leveling procedures for vertical control. The horizontal control surveys, as well as the trigonometric level surveys, established initial and subsequent coordinates and elevations by measuring angles and distances from control points SC-1 and SC-2

to the monuments in the network. Although SC-1 and SC-2 were located within the brinefield boundaries, their stability was verified before each survey by using trilateration and differential leveling procedures from control points P-1, P-2, and P-3, which were located on stable ground away from the brinefield. The Bureau began surveying the network in June 1979 and continued through February 1983. A total of 17 vertical and 12 horizontal control surveys were performed.

maximum vertical settlement measured was 1.58 ± 0.04 ft at R-15. From R-16 to R-39 (fig. 14) the subsidence was concentrated in the vicinity of the two sinkholes, with less movement at the midpoint between sinkholes. Vertical settlement in the area around R-16 was 0.18 ± 0.04 ft; settlement in the area around the midpoint between sinkholes (R-26) was 0.09 ± 0.04 ft; and settlement in the area around R-39 was 0.24 ± 0.04 ft. Data from R-40 to R-58 (fig. 15) showed that the

Results--Vertical Movement

The results from the vertical control surveys indicated that both sinkholes experienced vertical settlements between June 1979 and February 1983. Appendix A contains data from the final vertical control survey of the Carey brinefield; these data were used to calculate the maximum vertical displacements of the subsidence monuments.

Data from the R-line indicated that vertical settlements occurred between monuments R-7 and R-50. From R-4 to R-15 (fig. 13) the settlements increased linearly, starting at monument R-8 and continuing toward the well 50 sinkhole. The

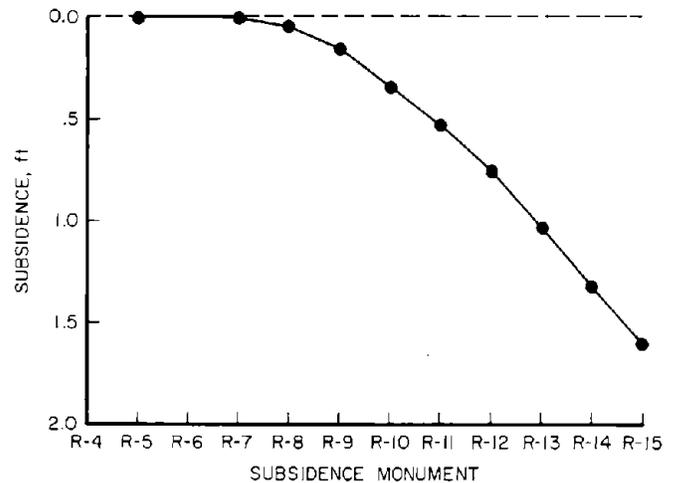


FIGURE 13.—Subsidence from R-4 to R-15.

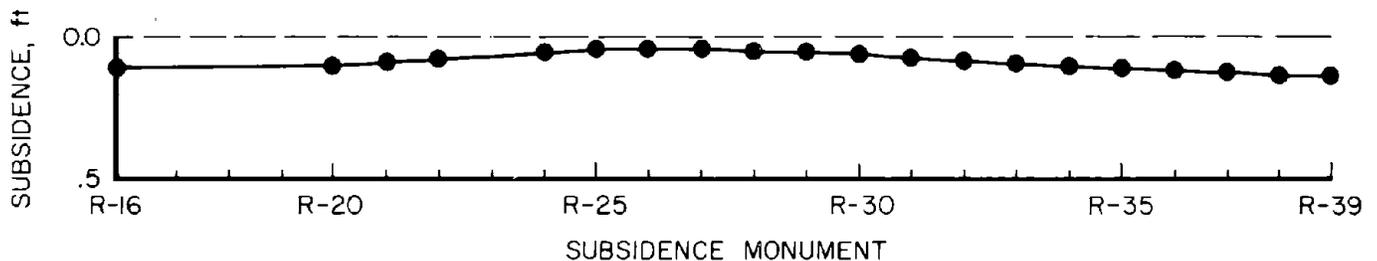


FIGURE 14.—Subsidence from R-16 to R-39.

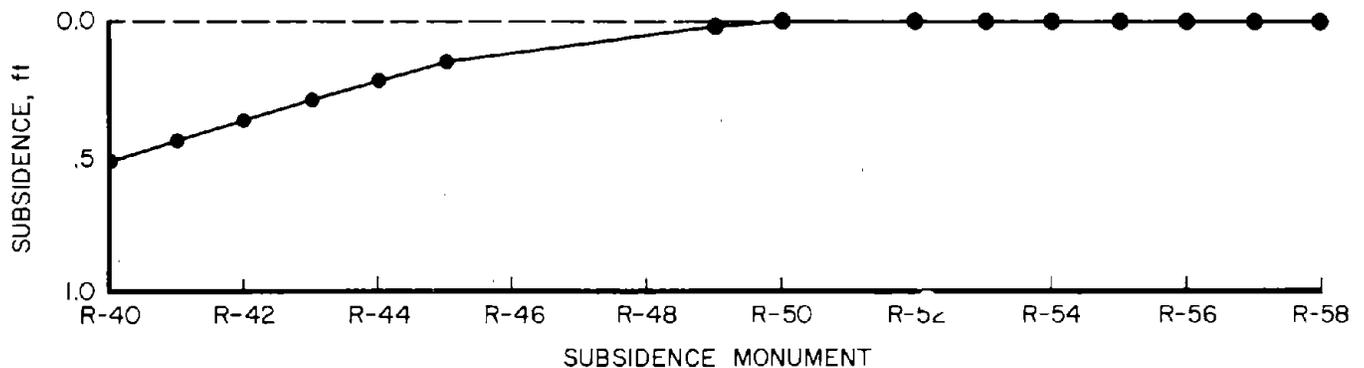


FIGURE 15.—Subsidence from R-40 to R-58.

settlement around the well 57 sinkhole began at R-49 and linearly increased toward the center of the sinkhole. The maximum settlement measured was 0.49 ± 0.04 ft at R-40.

The S-line showed vertical settlement between S-5 and S-20. The line from S-1 to S-12 began movement at S-6 and continued to linearly increase to S-12 (fig. 16). Maximum subsidence of 1.81 ± 0.04 ft was measured at monument S-12. Data from S-13 to S-21 (fig. 17) showed that movement began at S-20 and continued to linearly increase to S-13. The maximum subsidence at S-13 was 0.20 ± 0.04 ft.

Data from the T-line indicated that vertical settlements occurred between T-8 and T-19. The line T-1 to T-12 (fig. 18) experienced movements that started at approximately T-9 and linearly increased to T-12; the maximum subsidence at T-12 was 0.23 ± 0.04 ft. The line from T-13 to T-19 (fig. 19) showed movement that began at approximately T-18 and continued to linearly increase to T-13, where a movement of 0.34 ± 0.04 ft was measured.

Results--Horizontal Movement

The results from the horizontal surveys indicated that minor horizontal movements occurred in the vicinity of the well 50 sinkhole. However, the data from the surveys were inconclusive as to whether any movement had occurred around the well 57 sinkhole. Any possible movements along the R-line from R-16 to R-58, from S-13 to S-21, and the entire T-line were of a magnitude less than could be detected by the surveys; the minimum observable movement was calculated to be ± 0.35 ft. Appendix B contains data from the final horizontal control survey of the Carey brinefield; these data were used to calculate the maximum horizontal displacements of the subsidence monuments.

The R-line monuments underwent horizontal displacements oriented along the line from approximately R-10 to R-14 (fig. 20). The movement increased linearly in the direction toward the well 50 sinkhole. The movement at R-14 was approximately 1.0 ± 0.35 ft.

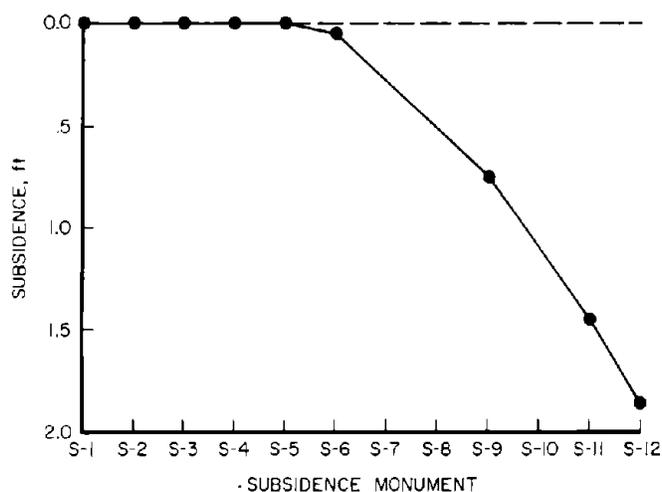


FIGURE 16.—Subsidence from S-1 to S-12.

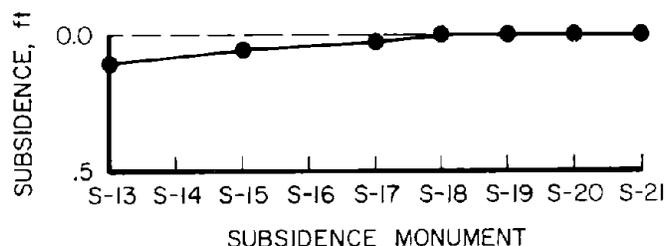


FIGURE 17.—Subsidence from S-13 to S-21.

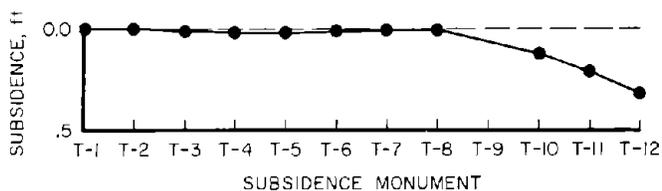


FIGURE 18.—Subsidence from T-1 to T-12.

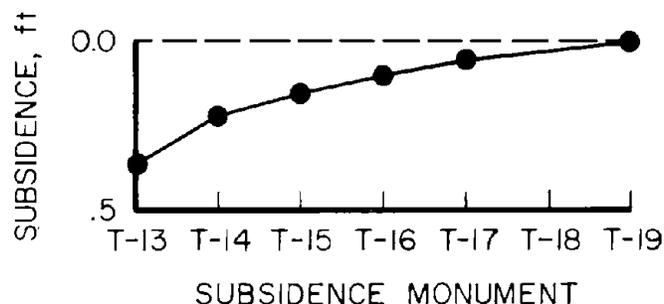


FIGURE 19.—Subsidence from T-13 to T-20.

The S-line monuments underwent horizontal movements that started at approximately S-5 and continued through S-12 (fig. 21). The movement was oriented along the line and increased linearly toward the well 50 sinkhole.

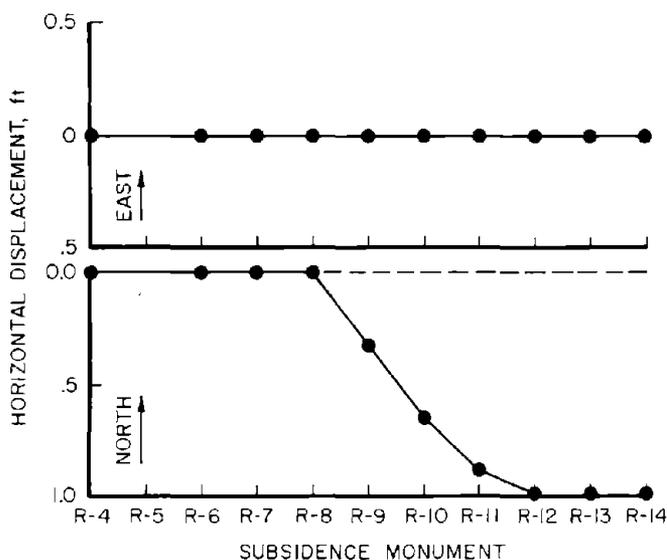


FIGURE 20.—Horizontal movement of R-4 to R-15.

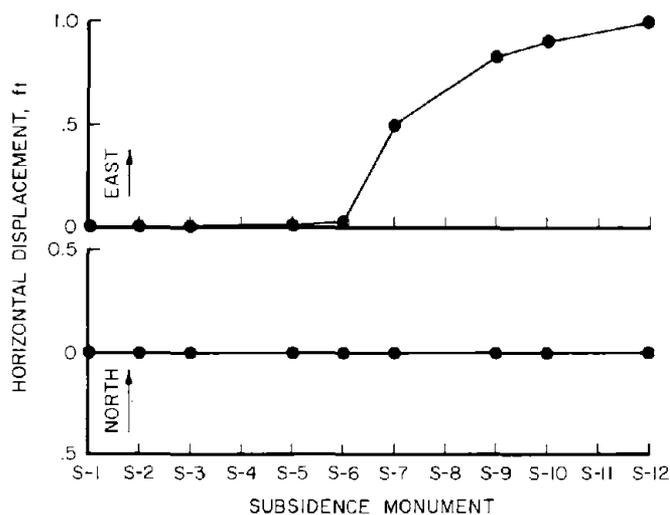


FIGURE 21.—Horizontal movement of S-1 to S-12.

The maximum horizontal movement at S-12 was measured to be approximately 1.0 ± 0.35 ft in the direction toward the sinkhole.

The results of the surveys taken on the T-line and the R-line from R-16 to R-58 were inconclusive as to whether any horizontal movement had taken place. If any movement did occur, it was of a magnitude less than could be ascertained by the results of the horizontal surveys.

CAREY WELL 56 (FOURTH INVESTIGATION)

Background

As part of the fourth investigation, the Bureau monitored a subsidence network in the vicinity of well 56 located at the Carey brinefield. This network was designed to detect any positional changes of the ground surface due to cavity failure around well 56. The network consisted of 19 Bureau-installed subsidence monuments.

Subsidence-Monitoring Network Design and Construction

The area around well 56 was monitored by two perpendicular lines of subsidence monuments (fig. 9). The M-line (M-1 to M-9) was oriented in the east-west direction, and the N-line (N-1 to N-10) was oriented in the north-south direction. The intersection of these two lines occurred at well 56.

The design of the subsidence monuments used in the M-line and N-line was identical to that used for the monuments in the previous investigation (fig. 12). These monuments were installed by Carey personnel using the same techniques as were used by the Bureau in the third investigation.

Monitoring Procedures

As in the third investigation, the Bureau used trilateration and traverse surveying procedures for horizontal control of the subsidence-monitoring network, and trigonometric and differential surveying procedures for vertical control. The monitoring program began in May 1981 and continued through February 1983. Seven vertical and five horizontal surveys were performed.

Results

The data obtained from both the vertical and horizontal surveys indicated that

no apparent movement had occurred in the area around well 56 during the time of the fourth investigation. If any

movement did occur, it was of a magnitude less than could be detected by the surveys.

INTERPRETATION OF RESULTS

FIRST AND SECOND INVESTIGATIONS

The analyses of results for the first and second investigations were not performed by the Bureau and are therefore omitted from this report. The analyses can be found in publications by Hendron (1, 3-4) and Walters (6).

THIRD INVESTIGATION

The survey data indicate that the subsidence in the vicinity of the two sinkholes continued throughout the period of the investigation. The results from the exploratory drilling program indicate that sagging shale beds were resting on the roof-fall rubble pile in the well 57 solution cavity; owing to the similarity and proximity of the two wells it was inferred that the well 50 cavity roof was resting on the roof-fall rubble pile in the well 50 cavity. The behavior of the subsidence around the two sinkholes was therefore most likely a result of the gradual settling of the sagging shale beds that was caused by the continued consolidation of the rubble piles on which the shale beds rested. As the rubble piles gradually compacted, the overlying strata responded with a gradual downward deflection into the rubble-filled cavities. If the consolidation processes ceased, the subsidence would also gradually cease; however, the subsidence was not halted, implying that consolidation was still occurring in the two collapsed cavities at the end of the investigation. It is logical to assume that the consolidation processes occurring in the rubble piles will, at some point in time, be completed, and subsidence still occurring after the completion of the investigation will eventually decrease and stop.

The characteristics of the subsidence occurring over the two failed cavities

indicate that gradual yet significant settlement of the ground surface can be expected after the initial collapse of a solution cavity and the formation of a sinkhole. This conclusion is further supported by the continued settling of other major sinkholes in the region; the area around the 1952 Barton sinkhole, for example, is still experiencing some minor deformations (6). It is also logical to assume that a larger volume cavity with accompanying sinkhole will experience surface deformations of greater magnitude than a smaller volume cavity; a larger volume cavity will contain a larger rubble pile, and thus experience more initial collapse and eventual consolidation. This is evidenced by comparing the deformations occurring above the well 50 cavity and the smaller well 57 cavity.

The symmetry of the ground surface deformations around the two sinkholes was due to the geometries of the underlying cavities, since the subsidence areas were similar in plan to the probable cavity geometries. The subsidence around well 50 was found to extend approximately 190 ft on the north and west sides of the sinkhole. The area east of the sinkhole was affected by a drainage canal that runs north-south in the vicinity of well 50 (fig. 9); the canal and its effects on the subsidence around the well 50 sinkhole are explained later in this section. The well 57 sinkhole, however, did not have a similar ground surface deformation pattern. The subsidence around the well 57 sinkhole was elongated in the northeast-southwest direction and had a total span of approximately 570 ft. The span of subsidence in the southeast direction was about the same as the dimensions for the well 50 sinkhole subsidence pattern. This could have been the result of a cavity extending in the northeast-southwest direction, elongated by hydraulic connections to other brine

wells in the area. However, the drilling data cannot confirm or deny this possibility owing to the limited number of holes that were drilled. Since both well cavities were located in virtually identical geologic settings and were mined by similar methods, it is likely that the ground surface deformation patterns were the result of a consistent failure process that was dependent on the dimensions of the two cavities.

The results from the survey data also indicate that well 50 experienced more vertical movement than did well 57. Hendron (5, p. 31) suggests that stoping of the well 50 cavity apparently progressed higher into the overlying shale beds than did stoping of the well 57 cavity, owing to a larger, unsupported roof span in the well 50 cavity. This would have created a larger volume of rubble in the well 50 cavity. This larger rubble pile would consolidate to a greater degree and cause more vertical movement of the overlying shale beds that were resting on it. This in turn would create a sinkhole of greater vertical extent. The subsidence around the well 57 sinkhole, however, was found to have extended much farther horizontally than the subsidence around the well 50 sinkhole. As proposed earlier, this was possibly the result of an elongated solution cavity.

Much of the ground surface movement in the vicinity of the well 50 sinkhole consisted of both horizontal and vertical components, but it is estimated that virtually all of the ground surface movements contained both components. The horizontal movements around well 50 were always vectored toward the center of the sinkhole; it was toward the center where maximum vertical displacements were observed. The horizontal movement in the area of the well 50 sinkhole produced tensional strains which were vectored toward the area of maximum vertical movement. Since the well 57 sinkhole had formed under nearly identical conditions to those at the well 50 sinkhole, it was inferred that there had been horizontal components of movement accompanying the vertical deformations around well 57, although these movements would have been

much smaller in magnitude owing to smaller vertical movements.

The surveys also indicate that the ground surface between sinkholes had experienced considerable amounts of vertical deformation (with presumed accompanying horizontal deformation). The two solution cavities were known to be hydraulically connected (5, p. 4); this connection may have elongated the two cavities along the area of communication. When the two cavities failed, the elongations could have deformed the ground surface above them. This explanation would be in agreement with the characteristics of the elongated subsidence pattern around well 57 (fig. 9).

The drainage canal that runs north-south through the brinefield (fig. 9) arrested approximately 90 pct of the ground surface deformations caused by the well 50 sinkhole. The S-line from S-13 to S-21 was located entirely on the east side of the canal; the first portion of the S-line was located on the west side of the canal, along with the well 50 sinkhole. The canal is approximately 25 ft wide and 15 ft deep. This reduction in ground surface movement could be explained by the fact that the canal severed the communication of the top 15 ft of the surface soil. This would totally halt all tensional strains in the top 15 ft of the soil that were brought about by the formation of the sinkhole. The horizontal and vertical displacements that were measured would have been the result of the communication of the soil underneath the canal.

FOURTH INVESTIGATION

The results obtained from the drilling and coring programs indicated that there was no evidence of bed separations, sagging, or stoping of the roof shales above the well 56 solution cavity. The survey results verified these findings by indicating that virtually no ground surface movements had occurred in the monitored area. It was, therefore, concluded that the solution cavity was stable and not undergoing deformational stresses. Since the drilling and coring program found the

well 56 cavity to have a smaller roof span than the well 50 or well 57 cavities, it is apparent that smaller

horizontal cavity dimensions were responsible for creating stable cavity conditions for well 56.

CONCLUSIONS

The four investigations performed by the Bureau in cooperation with the SMRI were designed to determine the characteristics and parameters of sinkhole formation over solution-mined salt cavities. The results from the exploratory drilling and coring investigations indicated that the Cargill sinkhole, the Barton sinkhole, and the two Carey sinkholes all were the result of solution-cavity roof failures caused by large, unsupported roof spans and deteriorating shale roof rock. In the case of the Cargill sinkhole, the cavity roof rock was completely breached, forming a chimney that piped approximately 90,000 yd³ of surface soil into its interior. The overlying shales of the Barton and the two Carey solution cavities did not completely fail, resulting in these beds sagging and resting on the rubble piles in the solution cavities. The solution cavity of well 56 in the Carey brinefield appeared to be stable in that no sagging or major deterioration of the overlying shales had occurred.

The results of the surveying programs that monitored the ground surface around wells 50, 57, and 56 in the Carey brinefield indicated a relationship between cavity size and subsidence geometry. It was inferred from the drilling and coring program that the postfailure subsidence was due to the consolidation of the rubble piles on which the sagging shale beds rested.

It is evident after evaluating the surface monitoring and the drilling and coring data that the large, unsupported roof spans that ultimately failed were the result of the well completion and mining operation procedures used for each collapsed solution cavity. These methods allowed salt dissolution near the roofs of the cavities, creating the large, unsupported spans that eventually failed. The methods used for salt dissolution in the area have now been changed to prevent salt dissolution near the top of solution cavities so as to limit the dimensions of the cavity roofs. The resulting cavity configurations should be more stable.

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APPENDIX A.--FINAL VERTICAL CONTROL SURVEY OF CAREY BRINEFIELD

(Positive values correspond to downward movement)

Subsidence monument	Movement, ft ¹	Subsidence monument	Movement, ft ¹	Subsidence monument	Movement, ft ¹
M-1.....	0.02	R-19.....	NA	S-2.....	0.02
M-2.....	.00	R-20.....	0.22	S-3.....	.03
M-3.....	-.01	R-21.....	.13	S-4.....	.03
M-4.....	-.04	R-22.....	.11	S-5.....	.04
M-5.....	-.03	R-23.....	NA	S-6.....	.07
M-6.....	-.01	R-24.....	.11	S-7.....	NA
M-7.....	-.01	R-25.....	.09	S-8.....	NA
M-8.....	.00	R-26.....	.09	S-9.....	.75
M-9.....	.01	R-27.....	.16	S-10.....	NA
MV-1.....	.04	R-28.....	.10	S-11.....	1.44
MV-2.....	.01	R-29.....	.12	S-12.....	1.81
MV-3.....	-.01	R-30.....	.15	S-13.....	.20
MV-4.....	.02	R-31.....	.12	S-14.....	NA
MV-5.....	-.01	R-32.....	.14	S-15.....	.15
MV-6.....	NA	R-33.....	.16	S-16.....	NA
MV-7.....	.04	R-34.....	.18	S-17.....	.09
N-1.....	-.01	R-35.....	.29	S-18.....	.08
N-2.....	-.02	R-36.....	.23	S-19.....	.04
N-3.....	-.02	R-37.....	.23	S-20.....	.04
N-4.....	-.04	R-38.....	.26	S-21.....	.03
N-5.....	-.02	R-39.....	.24	T-1.....	.04
N-6.....	-.04	R-40.....	.49	T-2.....	.04
N-7.....	-.01	R-41.....	.42	T-3.....	.05
N-8.....	-.01	R-42.....	.32	T-4.....	.05
N-9.....	-.02	R-43.....	.30	T-5.....	.04
N-10.....	-.02	R-44.....	.30	T-6.....	.05
R-4.....	NA	R-45.....	.27	T-7.....	.01
R-5.....	.03	R-46.....	NA	T-8.....	.02
R-6.....	NA	R-47.....	NA	T-9.....	NA
R-7.....	.03	R-48.....	NA	T-10.....	.08
R-8.....	.05	R-49.....	.07	T-11.....	.14
R-9.....	.13	R-50.....	.04	T-12.....	.23
R-10.....	.37	R-51.....	NA	T-13.....	.34
R-11.....	.52	R-52.....	.02	T-14.....	.21
R-12.....	.74	R-53.....	.03	T-15.....	.15
R-13.....	1.03	R-54.....	.03	T-16.....	.10
R-14.....	1.31	R-55.....	.02	T-17.....	.05
R-15.....	1.58	R-56.....	.01	T-18.....	NA
R-16.....	.18	R-57.....	.01	T-19.....	.02
R-17.....	NA	R-58.....	.01	T-20.....	NA
R-18.....	NA	S-1.....	-.02		

NA Not available.

¹Movement is elevation change between initial and final surveys.

NOTE.--Survey accuracy is ± 0.04 ft. The error limits were determined by statistically averaging the standard deviations of stable subsidence monuments for all surveys.

APPENDIX B.--FINAL HORIZONTAL CONTROL SURVEY OF CAREY BRINEFIELD

(Positive values correspond to increasing easting or northing)

Subsidence monument	Δ Easting, ft ¹	Δ Northing, ft	Subsidence monument	Δ Easting, ft ¹	Δ Northing, ft
M-1.....	-0.17	0.04	R-19.....	NA	NA
M-2.....	-.19	.02	R-20.....	0.22	-0.20
M-3.....	-.06	.05	R-21.....	.11	-.09
M-4.....	-.14	.04	R-22.....	.23	1.61
M-5.....	-.20	.01	R-23.....	NA	NA
M-6.....	-.16	.02	R-24.....	.20	.17
M-7.....	-.06	.10	R-25.....	.14	.18
M-8.....	-.06	.11	R-26.....	.19	.03
M-9.....	-.04	.14	R-27.....	-.11	.49
MV-1.....	.09	.03	R-28.....	.17	-.02
MV-2.....	.07	.03	R-29.....	NA	NA
MV-3.....	.06	.03	R-30.....	.31	.09
MV-4.....	.11	.23	R-31.....	.13	-.03
MV-5.....	NA	NA	R-32.....	.20	-.08
MV-6.....	NA	NA	R-33.....	NA	NA
MV-7.....	.01	.04	R-34.....	.27	-.08
N-1.....	-.07	.05	R-35.....	-.02	.87
N-2.....	-.29	.00	R-36.....	.25	-.05
N-3.....	-.16	.03	R-37.....	.22	-.08
N-4.....	-.18	.02	R-38.....	.29	-.13
N-5.....	.01	.08	R-39.....	.05	-.04
N-6.....	-.22	-.01	R-40.....	-.22	.09
N-7.....	-.11	.05	R-41.....	.06	.07
N-8.....	-.16	.02	R-42.....	.04	.14
N-9.....	-.03	.12	R-43.....	.08	.13
N-10.....	-.12	.05	R-44.....	.14	.16
R-4.....	.26	.02	R-45.....	NA	NA
R-5.....	NA	NA	R-46.....	.15	.11
R-6.....	.26	.01	R-47.....	NA	NA
R-7.....	.22	-.04	R-48.....	NA	NA
R-8.....	.17	-.18	R-49.....	.26	.05
R-9.....	.22	-.40	R-50.....	.28	.01
R-10.....	.13	-.57	R-51.....	NA	NA
R-11.....	.17	-.62	R-52.....	.28	.06
R-12.....	.26	-.82	R-53.....	.28	.04
R-13.....	.01	-1.00	R-54.....	.61	.26
R-14.....	.13	-.97	R-55.....	.33	.08
R-15.....	NA	NA	R-56.....	.31	-.02
R-16.....	NA	NA	R-57.....	.20	.00
R-17.....	NA	NA	R-58.....	.25	.00
R-18.....	NA	NA	S-1.....	.26	.04

See footnotes at end of appendix.

(Positive values correspond to increasing easting or northing)

Subsidence monument	Δ Easting, ft ¹	Δ Northing, ft	Subsidence monument	Δ Easting, ft ¹	Δ Northing, ft
S-2.....	0.31	0.13	T-1.....	0.34	-0.15
S-3.....	.26	.09	T-2.....	.34	-.15
S-4.....	NA	NA	T-3.....	.33	-.15
S-5.....	.27	-.02	T-4.....	.21	-.27
S-6.....	.36	.08	T-5.....	.28	-.09
S-7.....	.45	.06	T-6.....	.30	-.12
S-8.....	NA	NA	T-7.....	.23	-.05
S-9.....	.85	.09	T-8.....	.26	-.07
S-10.....	.97	.30	T-9.....	NA	NA
S-11.....	NA	NA	T-10.....	.31	.04
S-12.....	1.12	-.09	T-11.....	.32	.00
S-13.....	-.04	-.11	T-12.....	.30	.02
S-14.....	-.06	-.46	T-13.....	.04	-.19
S-15.....	.01	-.17	T-14.....	.08	-.06
S-16.....	NA	NA	T-15.....	.06	.04
S-17.....	.14	-.15	T-16.....	.04	.06
S-18.....	.17	-.13	T-17.....	-.70	-.14
S-19.....	.17	-.07	T-18.....	NA	NA
S-20.....	.13	-.14	T-19.....	.05	.04
S-21.....	.13	-.12	T-20.....	NA	NA

NA Not available.

¹Movement is change in horizontal coordinates between initial and final surveys.

NOTE.--Survey accuracy is ± 0.35 ft. The error limits were determined by statistically averaging the standard deviations of stable subsidence monuments for all surveys.

