# Geologic Studies Project Gnome Eddy County, New Mexico

GEOLOGICAL SURVEY PROFESSIONAL PAPER 589

*Prepared on behalf of the U.S. Atomic Energy Commission*

Cavity produced by the Gnome explosion and subsequent collapse. Note figure right-center of rubble for scale. Cavity is 70 feet high and more than 150 feet across. Photograph by Lawrence Radiation Laboratory.

GEOLOGIC STUDIES, PROJECT GNOME
EDDY COUNTY, NEW MEXICO

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*By* LEONARD M. GARD, Jr.

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# GEOLOGIC STUDIES, PROJECT GNOME, EDDY COUNTY, NEW MEXICO

By Leonard M. Gard, Jr.


## ABSTRACT

For Project Gnome, part of the Plowshare Program to develop peaceful uses for nuclear energy, a nuclear device was detonated December 10, 1961, underground in rock salt of the Permian Salado Formation southeast of Carlsbad, N. Mex.

The Geological Survey's investigations on behalf of the U.S. Atomic Energy Commission provided basic geologic and geophysical information needed to define preshot and postshot geologic and hydrologic conditions at and near the site. This report describes the geology of the site, some physical and chemical properties of the rocks, and the known effects of the nuclear detonation on the rocks of the site.

Geologic strata at the Gnome site consist of evaporite and clastic rocks of the Salado and Rustler Formations and Dewey Lake Redbeds, all of Late Permian age, the unconformably overlying Gatuna Formation of Pleistocene(?) age, and a cover of alluvial and eolian sands. All rocks, except where distorted by solution collapse, are nearly flat lying.

The evaporite deposits are easily dissolved and either are missing at the surface or only partially crop out in southeastern New Mexico; thus the sinking of a 1,200-foot shaft at Project Gnome provided an excellent opportunity to study these formations in detail. The strata were measured, sampled, and photographed while the shaft was being sunk.

The upper one-third of the Salado is exposed in the shaft and consists of 490 feet of bedded halite containing a few interstratified beds of clayey halite, anhydrite, polyhalite, and clay. The halite is overlain by a leached member comprised of 58 feet of clay, silt, gypsum, and anhydrite, much of which is a rubbly solution breccia.

The Rustler Formation disconformably overlies the Salado Formation. The five members of the Rustler are: lower member, 128 feet of silt and clay containing a few beds of gypsum; Culebra Dolomite Member, 28 feet of vesicular dolomite; Tamarisk Member, 113 feet mainly of beds of anhydrite partly hydrated to gypsum and a few thin beds of clay; Magenta Member, 21 feet of red-purple silty gypsiferous dolomite; and Forty-niner Member, 67 feet of anhydrite and gypsum.

The Dewey Lake Redbeds overlies the Rustler Formation with apparent conformity. These rocks are thinly laminated pale-reddish-brown siltstone displaying light-greenish-gray "reduction spots."

The Gatuna Formation of Pleistocene(?) age unconformably overlies the Dewey Lake Redbeds and consists of 49 feet of friable, poorly consolidated fine-grained sandstone and thin beds of clay, silt, and conglomerate. The Gatuna is in turn unconformably overlain by 43 feet of Recent alluvial bolson deposits, which are partly eolian and partly colluvial sand.

Mapping disclosed that deposition of the evaporite deposits was cyclical and resulted from repeated incursions of fresh sea water. Each cycle customarily begins with a bed of polyhalite, grades upward into pure halite, and ends with a clay-bearing halite at the base of the next higher polyhalite.

Comparison of preshot and postshot velocities in the salt near the shotpoint indicated that rock fracturing caused by the explosion was detectable from changes in elastic moduli, but compaction was not. No change in density of the rock could be detected.

The explosion formed a cavity about 70 feet high and more than 150 feet across. Postshot mining exploration revealed geologically interesting phenomena that resulted from the explosion. Intrusive breccia veins associated with complex thrust faulting were formed adjacent to the cavity. The breccia is composed of blocks of granulated and plastically deformed salt in a matrix of black melted salt. The black color of the matrix is due to the presence of laurionite, galena, and carbon. These materials, not present in the preshot rocks, were created by the shot. Lead from near the device combined with water and chlorine from salt to form laurionite and with sulfur from polyhalite to form galena. The carbon probably was derived from organic material present in the device chamber at shot time.

Lateral displacement of an instrument in a drill hole 100 feet from the shotpoint was about 16 feet. Strata 200 feet above the shotpoint were permanently displaced upward 5 feet, and a bed 55 feet below the shotpoint was displaced downward more than 10 feet.


## INTRODUCTION

### PURPOSE OF PROJECT GNOME

Project Gnome was a multiple-objective experiment conducted by the U.S. Atomic Energy Commission as part of the Plowshare Program to develop peaceful uses for nuclear explosives. Gnome was the first nuclear detonation within the continental limits of the United States outside of the Nevada Test Site since the Trinity shot in 1945.

The Project Gnome experiment consisted of the detonation of a nuclear device of about 3 kilotons equivalent TNT yield at a depth of about 1,200 feet below the surface in a thick salt deposit. The Gnome site is in the Nash Draw quadrangle in the approximate center of sec. 34, T. 23 S., R. 30 E., in Eddy County, and about 25 miles southeast of Carlsbad, N. Mex. (fig. 1).

The objectives of the experiment were fivefold (U.S. Atomic Energy Comm., 1961):

1. To explore the feasibility of converting the energy from a nuclear explosion into heat for the production of electric power.

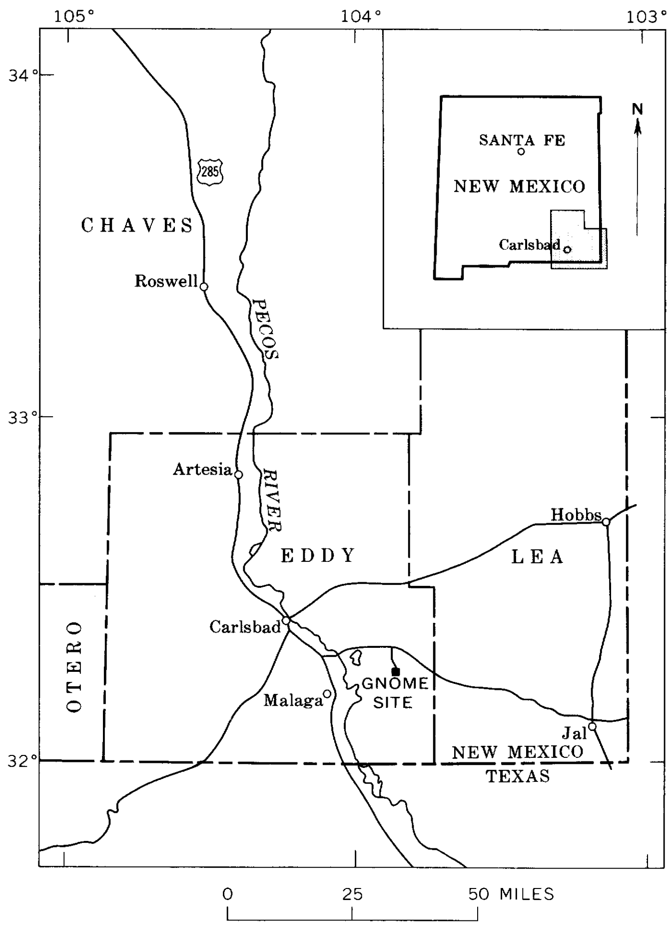



FIGURE 1.—Location of Project Gnome site, Eddy County, N. Mex.

2. To investigate the practicality of recovering useful radioisotopes for scientific and industrial applications.
3. To expand the data on characteristics of underground nuclear detonations to a new medium (salt), which differs markedly from the test media of the Nevada Test Site in which previous underground shots had been fired.
4. To make neutron cross-section measurements to contribute generally to scientific knowledge and to the reactor-development program.
5. To provide scientific and technical information on design principles useful in developing nuclear-explosive devices specifically for peaceful purposes.

## HISTORICAL SUMMARY OF THE PROJECT

The Gnome shot was detonated on December 10, 1961. It was the culmination of planning and site selection that started in 1958 when a study was begun by the U.S. Geological Survey to locate a site that would satisfy both technical and public-safety requirements. The required site was to have a deposit of relatively pure salt not more than 800 feet underground, to be within the continental United States, preferably on land controlled by the U.S. Government, and to be in an area having a low population density.

The Gnome site was selected after all possible sites in the United States had been thoroughly evaluated. Subsequently, a preliminary investigation of this area was undertaken by the Geological Survey. The surface and subsurface geology of the area was studied (Baltz, 1959; Moore, 1958a, b; Cooper, 1960, 1961, 1962; Jones, 1960; Vine, 1960, 1963); the regional ground-water conditions were appraised (Hale and Clebsch, 1959); the chemical and physical properties of salt were investigated (Morey, 1958; Harry Hughes, written commun., 1959; E. C. Robertson, A. R. Robie, and K. G. Books, written commun., 1958); the seismic properties of the salt were measured and compared with those of other rock types (Byerley and others, 1960; Roller and others, 1959); and a large-scale topographic map of the Gnome site was constructed.

This report describes the geology, hydrology, and physical, chemical, and optical properties of rocks at the site.

Shaft sinking began in July 1960 and was completed to a depth of 1,200 feet in May 1961. The Gnome shaft penetrates rocks of Permian and younger age. The shaft, circular in plan, has a finished diameter of 10 feet and is lined with reinforced concrete from the surface to a depth of 722 feet. The 1,000-foot drift was mined during the summer of 1961.

## PARTICIPATION BY THE U.S. GEOLOGICAL SURVEY

The U.S. Geological Survey made scientific studies and investigations related to Project Gnome on behalf of the Atomic Energy Commission. The Survey acted as agency advisor and provided technical support, largely with respect to public-safety aspects. The broad objectives of the Geological Survey's program were (1) to provide the basic geologic and geophysical information needed to define the preshot and postshot geologic and physical properties of the salt and other rocks affected by the explosion, and (2) to provide geologic and hydrologic information on the preshot and postshot hydrologic conditions at the Gnome site and surrounding region.

This report does not attempt to describe all the geologic effects produced by the Gnome explosion. Other agencies have studied close-in surface effects (Hoy and Foose, 1962) and the environment created by the explosion (Rawson, 1963; Rawson and others, 1965).

### PURPOSE OF THIS REPORT

This report describes the geology of the site, some physical and chemical properties of the rocks, and the effects, as far as they are known, of the nuclear detonation on the rocks at the site. It is based on studies that were carried out between July 1960 and June 1962.

### ACKNOWLEDGMENTS

For their friendly cooperation and many kindnesses, the Geological Survey personnel on the Gnome Project thank the personnel, too numerous to mention individually, of the Atomic Energy Commission; Holmes and Narver, Inc.; Lawrence Radiation Laboratory; Reynolds Electrical and Engineering Co.; and Cementation Co. of America, Inc.

### METHODS OF STUDY

The rocks in the shaft were measured, described (detailed measured section, p. 24), and sampled on a noninterference basis by L. M. Gard and W. A. Mourant during construction of the shaft. This was done as final mucking after each round was completed and before drilling for the next round began. Depending on the efficiency of the blasting, a round advanced the shaft 3–6 feet.

During this construction a section of the north wall was washed down and photographed in color. Unusual geologic features noted elsewhere in the shaft wall were also photographed and described. A complete photographic log in color is available for inspection at the Field Records and Photo Library, U.S. Geological Survey in Denver.

The geology of the preshot drift (pl. 1) was mapped by L. M. Gard and C. G. Bowles, using steel tape, at a scale of 1 inch to 10 feet; vertical and horizontal control was established by Holmes and Narver, Inc. In the underground mapping, projections of both left and right ribs (walls) were used. (Left and right are identified as one faces the shotpoint.) The rib projections are rotated outward to the horizontal plane along the line that joins their bases to the sill (floor). The back (roof) was not mapped, because it displayed very few mappable geologic features.

The geology of the postshot workings (pl. 2) was mapped by L. M. Gard and W. L. Emerick, assisted by W. H. Laraway, M. L. Schroeder, and John Moreland, Jr. The method was the same as that used in preshot mapping except that near the cavity, to expedite the work because of time limitations, the ribs were mapped continuously. Thus, the nine walls of the drilling alcove and parts of the approaching drift are represented by a single straight projection, and the corners are indicated for clarity in map presentation. Although the preshot drift was intact after the shot, it was not remapped because of high levels of radiation.

Prior to mapping both the preshot, and the postshot workings, the ribs were washed with water. The cleaned wet rock displayed additional stratigraphic details.

Elastic properties of the salt were determined underground, both before and after the shot, by D. D. Dickey and D. R. Cunningham. Preshot calculations were made by R. D. Carroll and D. D. Dickey, and postshot calculations were made by D. D. Dickey.

From his knowledge of the minor-element content in evaporite rocks of southeastern New Mexico, C. G. Bowles suggested and later supervised the determination of the minor elements in the salt beds of the preshot drift. B. M. Madsen made the petrographic descriptions of the preshot samples, Julius Schlocker studied the insoluble clastic material from these samples, and Theodore Botinelly determined the composition of the intrusive breccia formed by the explosion.

## GEOLOGY

### REGIONAL SETTING

The Gnome site is on the Mescalero pediment on the east side of the Pecos Valley, a section of the Great Plains physiographic province (Fenneman, 1931, fig. 1). The Pecos River flows through the southwestern part of this section and divides it physiographically into the Mescalero pediment to the east and the alluvial plain north of Malaga and the Gypsum Hills south of Malaga to the west.

The Gnome site is in the northeastern part of the Deleware basin (Adams, 1944; King, 1948; Newell and others, 1953). This deep structural basin, which is about 135 miles long and 75 miles wide, lies in southeastern New Mexico and west Texas and is generally considered to be the area surrounded by the Capitan Limestone (a reef limestone of Late and Early Permian age). The Capitan reef is horseshoe shaped, opening southward, and extends in the subsurface from Carlsbad eastward nearly to Hobbs, N. Mex., and thence southeastward into Texas (fig. 2). West and southwest of Carlsbad the Capitan Limestone is exposed and forms El Capitan Peak and part of the Guadalupe Mountains. Large caverns—notably Carlsbad Caverns—were formed in the reef limestone through the solvent action of circulating ground water.

The Delaware basin was submerged in Permian time (230–280 million years ago, according to Kulp (1961)) and was filled with thousands of feet of sediment. Toward the end of Permian deposition in the basin, the

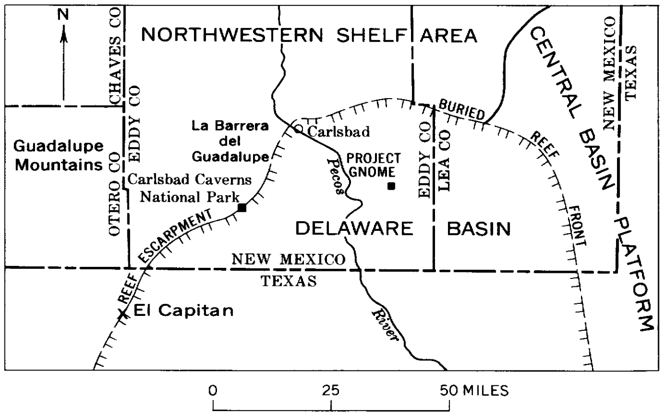



FIGURE 2.—Extent of the Delaware basin in New Mexico and adjacent structural and geographic features. Modified from King (1948) and Stipp and Haigler (1956).

reef growth around the basin was halted by increasing salinity of the sea water, and the evaporite rocks of the Castile, Salado, and Rustler Formations were deposited.

The Salado Formation, almost wholly salt, was deposited in a sea that extended from the Delaware basin across the Capitan reef zone many miles onto the shelf to the north. The southern end of this sea apparently had a restricted opening, and the consequent reduced circulation and outflow allowed evaporation to concentrate the sea water therein until salt was precipitated on the floor of the basin in southeastern New Mexico. The concentrated brine undoubtedly was replenished periodically by normal sea water; otherwise, the process would soon have ceased as the basin dried up. The salt beds of the Salado Formation grade southward into calcium sulfate and then into calcium carbonate facies, suggesting that the source of normal sea water lay in that direction and that the water became more concentrated as it moved northward.

After deposition of the evaporite rocks ceased, deposition of fine-grained terrestrial clastic sediment (Dewey Lake Redbeds) marked the close of the Permian. Terrestrial deposition continued during parts of Triassic time (181–230 million years ago), although subsequent erosion has removed Triassic beds from the Gnome area. Additional thin sediments accumulated in Quaternary time.

The evaporite rocks in the Delaware basin contain extensive deposits of potash minerals, which are mined at many localities. Many wells produce oil from the reef limestone in southeastern New Mexico and west Texas. Oil and gas are produced also from some of the deeper formations in the Delaware basin.

## GNOME AREA

The Gnome area referred to in this report is the square mile of sec. 34, T. 23 S., R. 30 E. (fig. 3). The land surface at the area is covered with as much as 43 feet of alluvial and windblown sand and caliche. More than 18,000 feet of sedimentary material ranging in age from Ordovician to recent underlies the Gnome site. Beneath the surface lie, in descending order, the Gatuna Formation of Pleistocene(?) age, the Dewey Lake Redbeds, and the Rustler and Salado Formations of Late Permian age. Beneath the Salado are thousands of feet of Paleozoic rocks which are not discussed in this report. All these formations are concealed by alluvium in the Gnome area, but all except the Salado crop out nearby (Vine, 1963).

Solution by ground water of salt at the top of the Salado Formation and of anhydrite within the Rustler Formation has removed thick sections of these rocks. A subsequent lowering of the land surface and differential collapse of the Rustler have formed many sinkholes and created a karst topography over much of this part of southeastern New Mexico. Nash Draw, about 6 miles to the northwest, is one of the largest depressions. Within Nash Draw are several smaller depressions, the largest of which is Laguna Grande de la Sal (Salt Lake).

The rocks dip gently to the east and southeast, and progressively younger formations are exposed in that

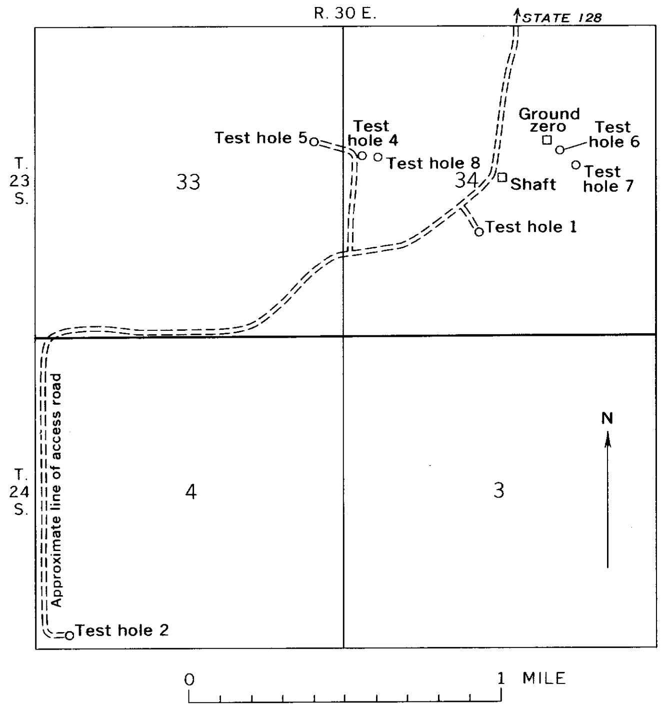



FIGURE 3.—Location of shaft, ground zero, and U.S. Geological Survey test holes at Project Gnome site.

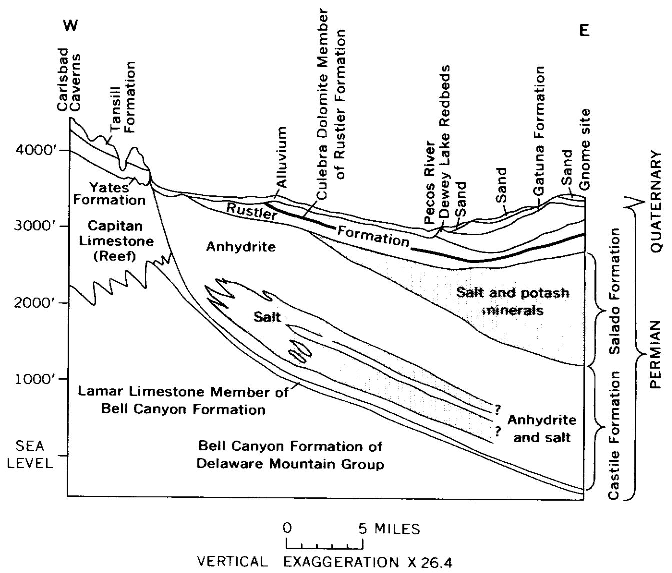



FIGURE 4.—Geologic section between Carlsbad Caverns National Park and Project Gnome site. Modified from Cooper (1960).

direction (fig. 4). Although the Salado Formation underlies an extensive area in southeastern New Mexico, no outcrops of it are known.

In many places the salt of the Salado Formation has been wholly or partially removed by solution. West of the Pecos River, very little salt remains; to the northwest over the buried Capitan reef, no salt is present; and south of the Gnome site, the Saldo salt is thin or absent over an area of nearly 100 square miles (Cooper, 1962). As much as 800 feet of salt has been removed. Within Nash Draw, solution has removed, and is presently removing, salt from the upper part of the Salado Formation.

The Rustler Formation crops out in numerous places west and northwest of the Gnome area and south of Malaga, a small town about 10 miles west of the area. The Dewey Lake Redbeds is exposed at several localities north and west of the Gnome area, especially along the margin of Nash Draw, and also crops out in a narrow discontinuous north-south belt a few miles east of the Pecos River. Triassic rocks are represented by the Santa Rosa Sandstone north of Nash Draw and southeast of the area; the Santa Rosa is not present, however, at the Gnome site. Unconsolidated Tertiary rocks crop out east of the area.

Quaternary rocks include the Gatuna Formation of Pleistocene(?) age, and alluvium, windblown sand, caliche, and playa lake deposits of Recent age. Alluvium occurs chiefly near the Pecos River north of Malaga. A recent report by Vine (1963) includes a geologic map of the Nash Draw quadrangle and stratigraphic sections of exposed rocks. The following generalized stratigraphic section (table 1) describes the rocks exposed in the Gnome shaft (fig. 5).

TABLE 1.—*Generalized stratigraphic section of rocks exposed in the Gnome shaft*

| Age | Unit | Lithology | Depth below surface (ft) | Thickness (ft) |
|---|---|---|---|---|
| Recent | Alluvial bolson deposits. | Unconsolidated sand. | 0 – 43 | 43.0 |
| Pleistocene(?) | Gatuna Formation | Friable sandstone and conglomerate. | 43 – 91.9 | 48.9 |
| Late Permian | Dewey Lake Redbeds. | Thin-bedded siltstone. | 91.9–294 | 202.1 |
| | Rustler Formation: | | | |
| | Forty-niner Member. | Chiefly gypsum and anhydrite. | 294 –361.3 | 67.3 |
| | Magenta Member. | Silty dolomite | 361.3–382.2 | 20.9 |
| | Tamarisk Member. | Chiefly anhydrite and gypsum. | 382.2–495.5 | 113.3 |
| | Culebra Dolomite Member. | Dolomite | 495.5–523.5 | 28.0 |
| | Lower member | Chiefly clay and silt, with some gypsum and anhydrite. | 523.5–651.2 | 127.7 |
| | Salado Formation: | | | |
| | Leached member. | Chiefly claystone and siltstone. | 651.2–709.3 | 58.1 |
| | Unleached part. | Chiefly impure halite rock, with some anhydrite, polyhalite, and siltstone. | 709.3–1,202 | 492.7 |
| | (Bottom of shaft.) | | | |

Structural deformation of the rocks is limited mainly to a gentle monocline in the Permian rocks and to collapse structures in the evaporite sections of the Permian rocks. No deeply buried faults are known. Locally, there are structural features related to the hydration of anhydrite to gypsum. This hydration considerably increased the volume of the affected rocks and caused them to be deformed, and in many places domed, where they are exposed at the surface (Vine, 1960).

## STRATIGRAPHY AT THE SITE

The following stratigraphic descriptions are supplemented by the detailed measured section at the end of the report (p. 24).

### SALADO FORMATION

At the Gnome site the Salado Formation is about 1,550 feet thick. More than 75 percent of the thickness of the Salado is salt, except where solution has thinned the formation. The remainder of the formation consists of potassium minerals and minor amounts of sandstone, siltstone, shale, anhydrite, and gypsum.

The bulk of the Salado is not known to contain ground water, although the leached member at the top of the formation is a brine aquifer locally. No free water has been reported to occur within the formation in the potash mines nor in the many drill holes throughout the

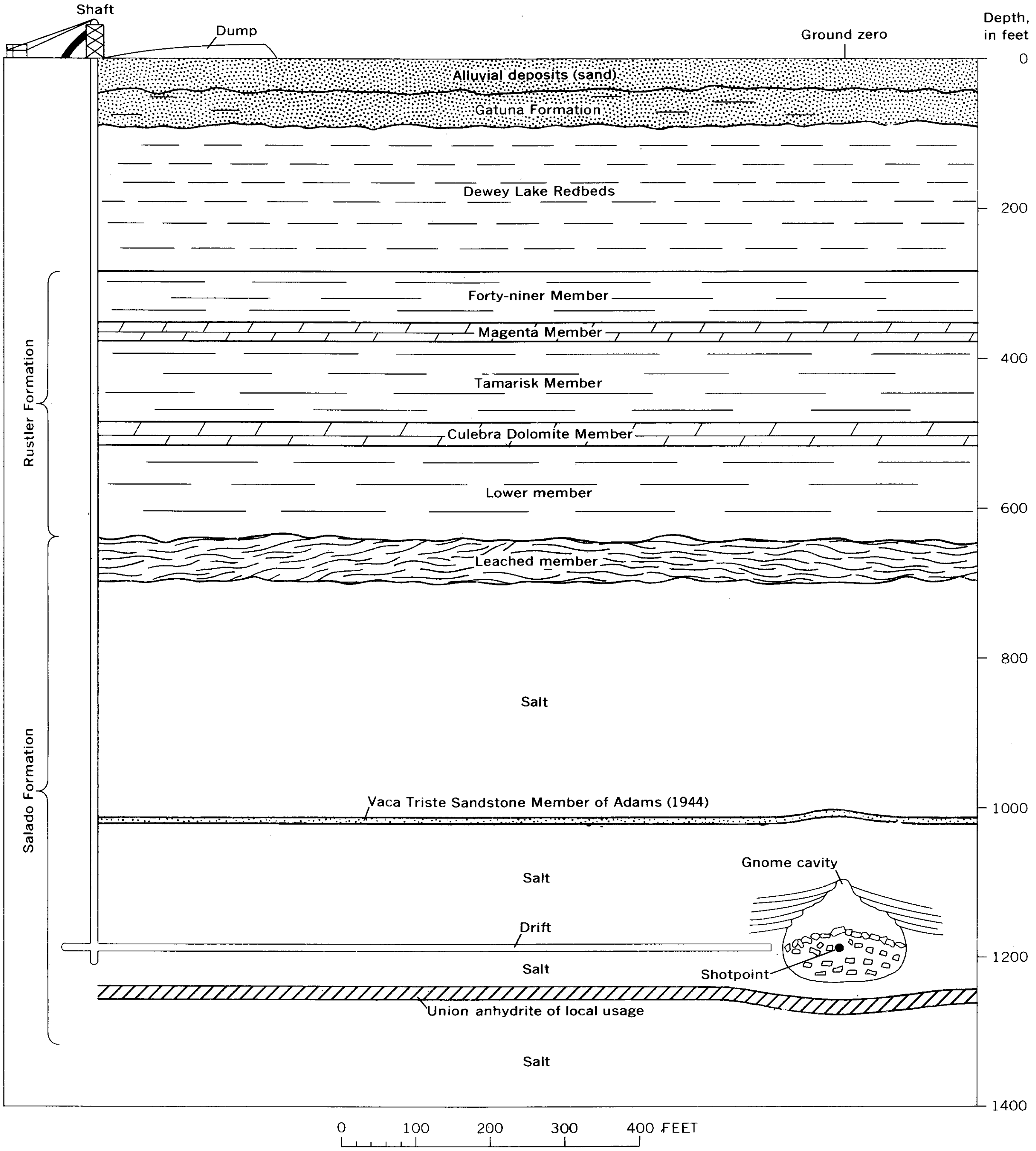



FIGURE 5.—Geologic cross section between shaft and cavity, Project Gnome site.

area. The halite rock is virtually impermeable because recrystallization of the salt restricts migrating fluids and prevents the formation of open spaces.

The shaft penetrated more than 490 feet of bedded halite that contains minor interstratified beds of clayey halite, anhydrite, polyhalite, and clay. The halite beds range in color from transparent colorless through white to reddish orange. The intensity of the orange color depends upon the amount of disseminated iron and polyhalite impurities present. The clayey halite beds range in color from reddish brown to greenish gray. The reddish-brown polyhalite beds, locally used as marker beds, average about 1 foot thick. They commonly have a thin bed of greenish-gray clay at the base. From 1,024.3 to 1,029 feet the shaft cut the Vaca Triste Sandstone Member of Adams (1944), a pale-reddish-brown clayey siltstone that forms a well-known marker unit.

The total thickness of the Salado Formation at the Gnome site has not been determined accurately, but data from nearby oil tests indicate that as much as 1,550 feet of the formation may be present (fig. 4).

The uppermost 58 feet of the Salado Formation consists of reddish-brown to gray clay and silt with a few interstratified gypsum and anhydrite beds. These strata represent, at least in part, an insoluble residue left after the removal of halite by ground water. This leached member or zone is estimated to be roughly one-third to one-tenth the thickness of the original halite rock that was present. The thickest unit of this leached zone is a solution breccia 36 feet thick. It is a heterogeneous rubbly mixture composed of siltstone, gypsum, and polyhalite blocks as much as 3 feet long set in a matrix of plastic grayish-red clay. In the shaft the leached zone did not contain water, although a small amount of water was detected in this zone in an observation well drilled about three-fourths mile west of ground zero (Gard and others, 1962, p. 121). Vine (1963, p. 8) reported that locally the leached zone is a prolific aquifer.

The top of the Salado Formation is considered by many geologists to be at the top of the uppermost halite bed, and the leached member is assigned to the Rustler Formation. This assignment is based partly on the fact that the Rustler Formation is reported to contain some salt beds to the southeast, and partly on the fact that the leached member cannot be distinguished from the lower member of the Rustler in either drill cuttings or geophysical logs. However, because the leached member was recognized as a distinct unit in the Gnome shaft and because it has a disconformable upper contact and contains several collapse breccia beds that are distinctly different from the lower member of the Rustler, it has been assigned in this report to the Salado Formation.

## RUSTLER FORMATION

The Rustler Formation of Late Permian age unconformably overlies the Salado Formation and is composed mainly of evaporite deposits of anhydrite (commonly altered to gypsum) and dolomite and contains some siltstone and clay in the lower part. The thickness of the Rustler at the shaft is 357.2 feet, although in nearby areas the thickness ranges from 90 to more than 500 feet.

The Rustler is divided into five members, all present in the Gnome shaft. The upper four members crop out near Nash Draw to the north and near the Pecos River to the west.

The lower, unnamed member of the Rustler Formation lies disconformably on the leached top of the Salado Formation. It is 127.7 feet thick and consists principally of poorly consolidated silt and clay and contains a few interstratified beds of gypsum.

The Culebra Dolomite Member overlies the lower member and consists of 28 feet of yellowish-gray generally microcrystalline dolomite. It contains some massive zones, as well as as brecciated zones, that are recemented with pale-yellowish-brown dolomite. A characteristic feature of the Culebra is the presence of numerous small nearly spherical cavities that range from 1 to 20 mm in diameter. Some cavities are partly filled with secondary gypsum and calcite, but most are open. They do not appear to be interconnected. These cavities are thought to have originated either by solution of a highly soluble mineral aggregate or by the inclusion of gas or liquid when the sediment was soft (Vine, 1963, p. 14).

The Culebra Member is an artesian aquifer at the shaft, where it has a head of about 75 feet. The water appears to be contained in fractures and is confined above by the anhydrite and gypsum of the Tamarisk Member and below by clay of the lower member.

The Culebra is an excellent subsurface marker, because its lithology is unique in southeastern New Mexico. It is widespread in the Delaware basin and has been identified in many hundreds of drill holes. It is the principal aquifer at the Gnome site and yields water to wells in the western half of the project area. The depth to the top of the Culebra ranges from zero in the Nash Draw–Pecos River area to at least 1,200 feet in the eastern part of the State. The configuration of the top of the Culebra is similar to that of the top of the salt in the Salado Formation. Apparently, as salt in the Salado was removed by solution, the overlying beds settled and assumed, in general, the shape of the surface of the remaining salt.

The overlying Tamarisk Member is 113.3 feet thick and is composed mainly of beds of anhydrite partly hydrated to gypsum, but it contains some thin beds of clay.

The overlying Magenta Member is a red-purple (magenta) silty gypsiferous dolomite 20.9 feet thick. Although an aquifer in some places, it contains no water at the shaft.

The Forty-niner Member, like the Tamarisk Member, is composed mainly of anhydrite and gypsum. It is 67.3 feet thick in the shaft, but is missing in U.S. Geological Survey hydrologic test holes 4 and 5 about one-half mile west of the shaft (fig. 3). Whether removal of the Forty-niner Member was by erosion prior to deposition of the Dewey Lake Redbeds or by leaching subsequent to deposition is not known, although leaching is considered to be more likely.

The structure of the Rustler Formation is mildly undulating where these beds are 200–300 feet below the ground surface. Locally, however, solution and collapse have affected the formation where it is deeply buried. Generally the carbonate members—the Culebra and the Magenta—are the least affected by solution and are present throughout most of the area. At the Gnome site they are separated by more than 100 feet of the Tamarisk Member. In the Nash Draw area, solution and collapse have locally removed the entire Tamarisk, and the Magenta rests directly upon the Culebra.

### DEWEY LAKE REDBEDS

The Dewey Lake Redbeds of Late Permian age overlies the Rustler Formation with apparent conformity. The contact is marked by the abrupt color change from the white of the gypsum of the Forty-niner Member of the Rustler Formation to the red of the Dewey Lake.

The Dewey Lake is mainly made up of pale-reddish-brown siltstone that displays a polka-dot appearance, owing to the presence of light-greenish-gray reduction spots (round spots about 0.5 cm across where ferric iron has been reduced to ferrous iron). The formation is 202.1 feet thick in the shaft and is composed mainly of subangular to subrounded clear quartz grains and chert and feldspar grains in a clay matrix. Muscovite, biotite, rock fragments, and opaque minerals make up less than 10 percent of the mineral grains. Bedding consists of thin (0.5–1.5 mm) laminae and, less commonly, very small scale cross-laminations. Red clay forms 15–25 percent of the rock and is the principal cement, although calcite and gypsum are common. The Dewey Lake represents the beginning of detrital sedimentation following the long period of chiefly evaporite deposition in the Delaware basin and adjacent shelf areas in southeastern New Mexico.

### GATUNA FORMATION

The Gatuna Formation of Pleistocene(?) age unconformably overlies the Dewey Lake Redbeds and is pale-red to moderate-brown friable fine-grained sandstone, 48.9 feet thick in the shaft, that contains a few thin beds of clay and silt and many thin beds of conglomerate. The sand- and silt-sized material is mainly made up of quartz grains, and the pebbles are quartzite, limestone, and chert. The grains are weakly to moderately cemented with calcium carbonate. The presence, in several beds, of reworked fragments from the underlying Dewey Lake suggests that the Gatuna was deposited on a surface of considerable relief.

Elsewhere in the Nash Draw quadrangle (Vine, 1963), the Santa Rosa Sandstone of Triassic age lies between the Dewey Lake Redbeds and the Gatuna Formation, but it is missing at the Gnome site.

### ALLUVIAL BOLSON DEPOSITS

Alluvial bolson deposits of Recent age unconformably overlie the Gatuna Formation and are chiefly made up of unconsolidated moderate-brown fine-to medium-grained quartz sand. The upper 9 feet of these deposits is dune sand, but the lower 34 feet is partly eolian and partly colluvial. The sand has been derived from the Gatuna Formation and perhaps in part from the Ogallala Formation of Pliocene age, which may once have covered the area (Vine, 1963, p. 36). The top 3 feet of the lower 34 feet is weakly cemented by caliche, a near-surface accumulation of calcareous material, that was precipitated by subsurface evaporation of moisture in this semiarid region.

### STRUCTURE

The rocks penetrated by the shaft are nearly flat lying, although locally in the shaft the Rustler Formation dips steeply. The regional structure is a small homoclinal dip to the east (Vine, 1963, p. 37). In the shaft the Dewey Lake rocks strike N. 45° E. and dip about 5° NW. Bedding in the Salado Formation observed in the drift strikes N. 89° E. and dips 0°20′ N. The attitude of the bedding in the Salado Formation is locally variable. Information from a drill hole 500 feet south of ground zero suggests that the same beds may be as much as 10 feet higher in the drill hole than in the drift. Whether this difference is due to a local flexure or to an error in drilling observations is not known.

Fairly steep dips were observed in some beds of the Rustler Formation, especially in gypsum and anhydrite. Dips as high as 42° NW. were noted in a gypsum bed in the lower member of the Rustler. These anomalous attitudes are believed to be associated with volume changes that take place when anhydrite changes to gypsum or when solution differentially telescopes the rocks. The northwest dip observed in the Dewey Lake Redbeds may result from thinning of the underlying Rustler Formation to the west or northwest. As previously noted, the Forty-niner Member of the Rustler is completely missing in test holes drilled about half a mile west of the shaft.

## GEOLOGY OF THE PRESHOT GNOME DRIFT

The nuclear device was placed in a small chamber at the end of a drift (pl. 1) driven N. 50° E. from the bottom of the shaft. The drift was 1,223 feet long and included a curved section near the shaft. The end of the drift curved around a "buttonhook," doubling back on itself and ending at the device chamber. The device chamber was about 1,000 feet horizontally from the bottom of the shaft and slightly less than 1,200 feet below the ground surface. Thus, the rock cover over the detonation point consisted of about 500 feet of massive salt beds and about 700 feet of other sedimentary rocks. Below the detonation point was probably an additional 1,000 feet of bedded salt.

Only the Salado Formation is exposed in the drift; bedding strikes N. 89° E. and dips 0°20′ N. Owing to the low dips, the ribs (walls) of the drift were mapped to show geologic features that could not be included on an ordinary map (pl. 1). Mapping, done during July 1961, was on a scale of 1 inch to 10 feet to show the depositional features in the salt strata in some detail.

Eight mappable beds of halite rock containing varying amounts of clay and polyhalite and one mappable bed of polyhalite were transected by the drift. The nine beds were arbitrarily numbered in descending order from 10 to 18. Because the drift intersects the bedding at an angle of about 40° to the strike, the beds have a component of dip toward the device chamber; thus, the lowest beds are exposed near the shaft, and successively higher beds are exposed toward the device chamber. Total thickness of the exposed beds is about 22 feet. The following stratigraphic section (table 2) describes the beds in the Gnome drift.

Deposition of the Salado Formation was often cyclic, as indicated by the strata exposed in the drift. Ideally, a cycle begins with a polyhalite bed at the base, grades upward into halite containing polyhalite, and terminates with clay-bearing halite at the top. A cycle represents an incursion of fresh sea water that temporarily decreased the salinity of the brine and caused deposition of calcium sulfate. Concentration of the fresher sea water subsequently caused the precipitation of sodium chloride.

TABLE 2.—*Detailed stratigraphic section of Salado Formation along drift from device chamber to shaft*

| *Unit* | *Description* | *Thickness (ft)* |
|---|---|---|
| 120 | Polyhalite rock (marker bed 120), reddish-brown, microcystalline; varies in thickness because upper contact gradational into overlying halite. (Exposed in postshot workings.) | 0. 5–1. 5 |
| 10 | Halite rock, colorless to pale-orange; grain size 10–20 mm; bands 0.25–0.3 ft thick of colorless to milky halite alternate with 0.1- to 0.2-ft-thick bands of pale-orange halite containing disseminated orange polyhalite; 0.18-ft thick discontinuous band of orange polyhalite 1.2 ft below top of unit; polyhalite more concentrated in lower 1.5 ft; dark-gray clay layer 5.4 ft above base (clay seam in fig. 12); lower 0.8 ft contains 4 percent gray clay in thin horizontal streaks and bands; device set at base of this unit. (Only lower 4.3 ft exposed in preshot drift.) | 8. 0 |
| 11 | Halite rock, clear, gray, rarely brown, gray clay seam 0.05 ft thick at top; contains a few discontinuous bands of halite with disseminated polyhalite; displays ripple-mark casts where back of drift breaks to base of unit | . 2–1. 0 |
| 12 | Halite rock, light-gray to light-brown; clay content 10–50 percent; clay generally brown but some gray; base of unit a brown clay seam which at places truncates upturned beds of underlying unit | . 2–1. 0 |
| 13 | Halite rock; contains inclusions of brown clay; upper 2 ft contains irregular layers of brown clayey halite alternating with pale-orange to grayish-white halite; contains vertical mudcracks filled with clay, polyhalite, and secondary halite; layers between mudcracks near top of unit are concave upward; lower 1.5 ft light-brown halite with 20–25 percent inclusions and vertical streaks of brown clay; clay content decreases downward; contact with underlying unit gradational | 3. 5 |
| 14 | Halite rock, pale-orange to white; contains blebs and disseminated particles of orange polyhalite forming indistinct layers which are most noticeable in lower half | 3. 5–4. 0 |
| 15 | Polyhalite rock (marker bed 121), moderate-reddish-brown, microcrystalline; variable thickness usually due to irregularity of upper contract, which may be gradational; lower contact sharp | . 5–1. 0 |
| 16 | Halite rock, colorless to gray-green to pale-orange; 0.1 ft greenish-gray clay at top; upper 1.6 ft contains 20 percent gray-green clay and 3 percent polyhalite; clay content decreases downward; upper part contains pods and downward-tapering wedges of secondary halite containing gray-green clay and polyhalite | 4. 8 |
| 17 | Halite rock, colorless to light brown; 10 percent streaks and inclusions of brown clay. (Exposed only in blast-door alcove) | . 5 |
| 18 | Halite rock, colorless to light-brown; contains 2 percent brown clay and 2 percent polyhalite. (Exposed only in blast-door alcove.) Base not exposed | 3+ |
| | Total exposed thickness | 22+ |

One complete cycle of deposition and parts of two others are represented in the drift. The complete cycle began with the deposition of unit 15, the polyhalite bed, and ceased with the deposition of unit 13. Units 16–18 are part of the previous cycle, and units 10–12 are part of the subsequent cycle.

Polyhalite probably was not deposited from the original brine but was altered from gypsum or anhydrite

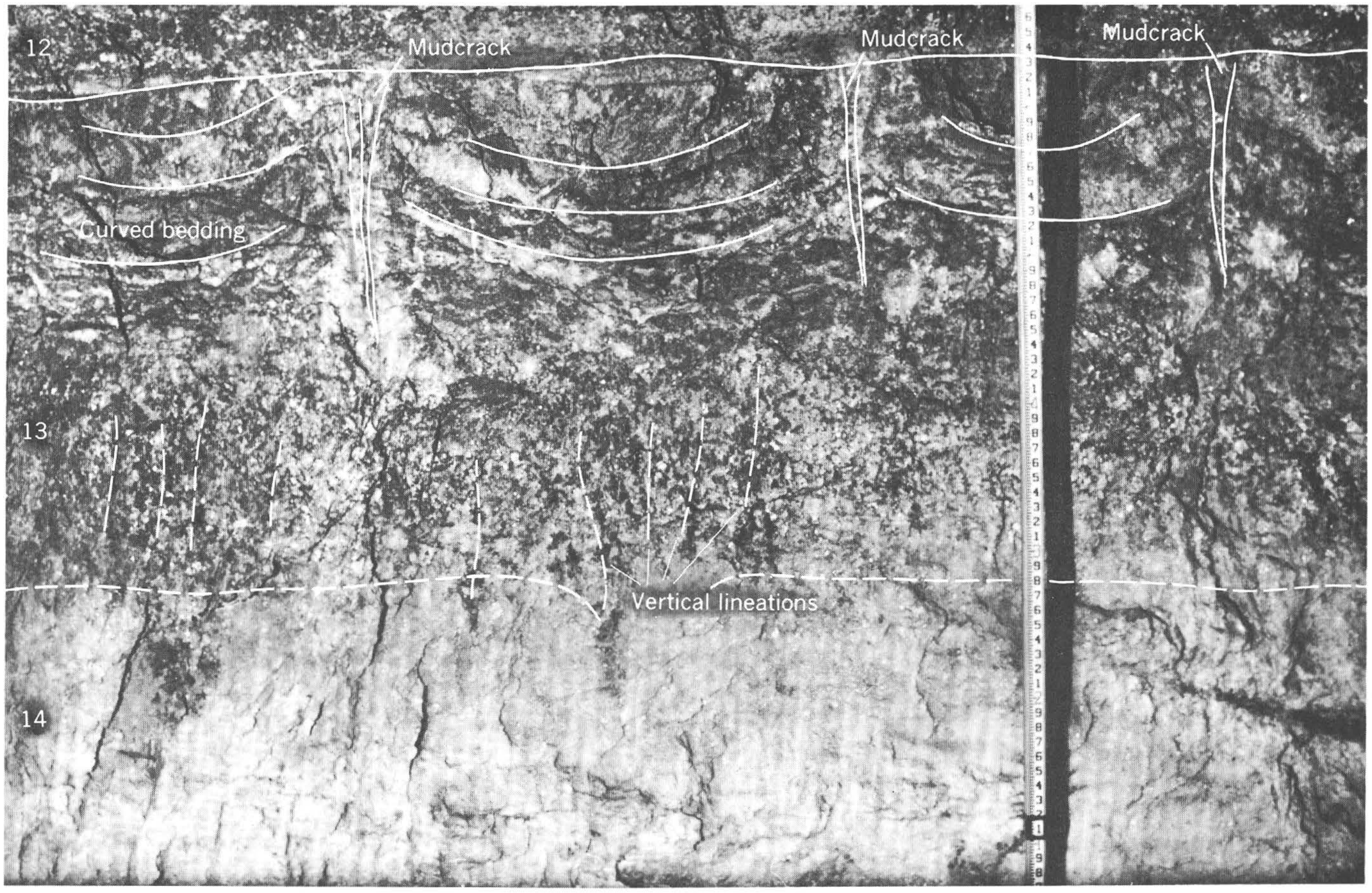



FIGURE 6.—Units 12, 13, and 14 exposed in preshot drift. Note mudcracks in unit 13 with curved bedding between, and vertical lineations at base of unit 13.

by the later addition of potassium and magnesium (Moore, 1958b, p. 14).

The polyhalite bed (unit 15), known locally as marker bed 121, is present in the Salado Formation over a wide area. Its sharp regular lower contact is underlain by a thin layer of greenish-gray clay. Thin clay layers underlie many of the polyhalite beds in the Salado Formation and are thought to have been concentrated by the re-solution of impure salt when the brine was freshened.

In places along the drift the polyhalite is underlain by pods of abnormally large halite crystals which contain disseminated gray clay and polyhalite. Whenever the pods are present, the underclay is absent. The gross halite crystals in these pods are thought to have resulted from secondary recrystallization.

Continued concentration of the brine by evaporation resulted in deposition of unit 14, which contains little or no clay but contains polyhalite blebs. Unit 14 is gradational upward into unit 13, which contains as much as 25 percent clay. Further evaporation, perhaps even to dryness, produced desiccation cracks in unit 13 (fig. 6). These cracks are filled with clay, halite, and polyhalite. In the upper part of this unit, bedding between the desiccation cracks is concave upward and resembles the cross section of curved polygonal plates that commonly develop between desiccation cracks. Most of these features were seen only in cross section; one polygonal structure, however, is well exposed in the back of the drift at station 4+35 and exhibits a typical 120° junction of three mud-filled cracks, one of which is traceable down the right rib. Another such junction is well exposed in the No. 12 lateral in the reentry drift. Probably this part of the basin either was evaporated to dryness or was locally uplifted to above sea level at this time. Desiccation cracks observed at several places in the shaft and in the core from a hole drilled at ground zero indicate recurrent complete evaporation during deposition of the Salado Formation. These cracks could, however, represent a time of local upwarp and subaerial exposure of a limited area rather than evaporation to dryness of the entire basin.

The clay in unit 13, which decreases downward, displays faint vertical brown clayey lineations, which may have been caused by downward percolation of rain water, if salt strata were exposed by local upwarp, or by sea water when the area was again submerged. This vertical lineation is clearly visible in figure 6.

Units 11 and 12 are very thin, aggregating generally less than a foot in thickness, and are separable only by the difference in color of their contained clay. Unit 11 is generally gray, and unit 12 is generally brown. The top of unit 12 and the bottom of unit 11 display current ripple marks in the back of the drift near station 5+45 where the underside of unit 12 is exposed in the back of the drift. The contact between units 12 and 13 is very sharp, and some of the upturned beds at the top of unit 13 appear to have been truncated by unit 12.

Precipitation of salt began again with the formation of unit 12; the brine was apparently concentrated enough so that sodium chloride was the first mineral deposited. In unit 10 alternating layers of colorless halite and orange halite (colored from the iron in disseminated polyhalite) suggest rhythmical freshening of the brine. The top bed of this cycle seen in the postshot workings and cavity walls is a polyhalite bed (marker bed 120) that lies only a few feet above unit 10 and indicates the beginning of a new depositional cycle.

## PROPERTIES OF THE ROCKS

To define the rocks surrounding and overlying the device chamber various properties were determined, both before and after the shot. Certain physical properties were determined both in the laboratory and in situ. Semiquantitative spectrographic analyses were made, and the petrography of the rocks exposed in the drift was studied.

These preshot determinations were made to provide a basis for postshot comparisons. It was found, however, that the shot had little effect on the bulk of the geologic medium, and, accordingly, detailed postshot analyses were made only in specific places on rocks close to the cavity.

### PHYSICAL PROPERTIES

Various physical properties were determined by the Geological Survey laboratories for 32 samples (tables 3, 4) collected from the Gnome shaft during construction. These samples are considered to be representative of the rocks overlying the device chamber.

Porosity, grain density, and dry-bulk density of the insoluble samples were determined by the water-saturation, mercury-displacement, and powder-grain methods. For water-soluble samples, kerosene was substituted for water, and the proper density corrections were made (table 3).

Dynamic elastic moduli were determined from calculations using torsional and flexural resonant frequencies of specimens (table 3). Static elastic moduli and compressive strength were measured on cores 1 inch in diameter and 2 inches long (table 4).

TABLE 3.—*Physical properties of rock samples from Gnome shaft*

[Analysts: D. R. Cunningham, John Moreland, Jr., and E. F. Monk. Asterisk (*) indicates $10^5$ psi (pounds per square inch); nd, not determined; .., not determined owing to insufficient sample]

| Geologic unit | Lithology | Depth (ft) | Porosity (percent) | Grain density (g per cc) | Dry-bulk density (g per cc) | Magnetic susceptibility ($10^{-6}$ cgs units) air dried | Sonic method: Young's modulus ($10^6$ psi) | Sonic method: Modulus rigidity ($10^6$ psi) | Sonic method: Poisson's ratio | Sonic method: Longitudinal velocity (ft per sec) | Sonic method: Transverse velocity (ft per sec) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gatuna Formation | Sandstone | 50– 70 | 31.9 | 2.66 | 1.81 | 36.9 | *5.38 | *2.64 | 0.0189 | 5,072 | 3,552 |
| Dewey Lake Redbeds | Siltstone | 95– 100 | 21.6 | 2.68 | 2.10 | 7.8 | nd | nd | nd | nd | nd |
| | do | 250 | 11.8 | 2.68 | 2.36 | 10.8 | nd | nd | nd | nd | nd |
| Rustler Formation: | | | | | | | | | | | |
| Forty-niner Member. | Anhydrite | 298 | 7.9 | 2.50 | 2.31 | 5.3 | 2.56 | 1.09 | .1743 | 10,825 | 6,816 |
| | do | 320 | 12.2 | 2.82 | 2.48 | 6.0 | 3.19 | 1.30 | .2269 | 10,223 | 6,076 |
| | Siltstone | 331 | 24.9 | 2.66 | 2.00 | 14.9 | 1.18 | *5.34 | .1028 | 6,836 | 4,548 |
| | Gypsum | 343 | 8.7 | 2.43 | 2.22 | 6.7 | 2.66 | 1.27 | .0472 | 10,715 | 7,386 |
| | Gypsum and anhydrite | 350 | 3.5 | 2.37 | 2.29 | 3.6 | 2.52 | 1.00 | .2600 | 11,275 | 6,421 |
| Magenta Member | Dolomite | 365 | 34.7 | 2.92 | 1.91 | 4.8 | *7.10 | *2.85 | .2456 | 5,587 | 3,244 |
| | Dolomitic siltstone | 370 | 22.7 | 2.81 | 2.17 | 7.9 | nd | nd | nd | nd | nd |
| | Dolomite | 380 | 19.1 | 2.91 | 2.35 | 4.1 | nd | nd | nd | nd | nd |
| Tamarisk Member | Gypsum and anhydrite. | 400 | 2.5 | 2.39 | 2.33 | 4.3 | 5.41 | 2.89 | .1812 | 15,205 | 9,487 |
| | Claystone | 482 | 22.1 | 2.68 | 2.08 | 6.2 | *9.39 | *3.71 | .2655 | 6,546 | 3,713 |
| Culebra Dolomite Member. | Dolomite | 505 | 12.5 | 2.85 | 2.49 | 5.8 | nd | nd | nd | nd | nd |
| | do | 515 | 12.3 | 2.83 | 2.48 | 2.1 | 2.96 | 1.28 | .1563 | 9,809 | 6,261 |
| Lower member | Claystone | 527 | 29.6 | 2.71 | 1.91 | 10.5 | nd | nd | nd | nd | nd |
| | Gypsum and anhydrite | 535 | 3.1 | 2.37 | 2.3 | 4.6 | 2.93 | 1.13 | .2965 | 12,706 | 6,834 |
| | Claystone | 552 | 25.1 | 2.68 | 2.01 | 8.2 | *8.41 | *3.40 | .2368 | 6,201 | 3,642 |
| | Siltstone | 590 | 21.3 | 2.71 | 2.13 | 19.1 | 1.34 | *5.98 | .1167 | 7,044 | 4,640 |
| | do | 620 | 19.3 | 2.70 | 2.17 | 7.7 | nd | nd | nd | nd | nd |
| Salado Formation | Claystone breccia (residuum). | 653 | 26.2 | 2.69 | 1.98 | 17.2 | nd | nd | nd | nd | nd |
| | Siltstone (residuum) | 693 | 1.1 | 2.15 | 2.13 | 5.8 | 1.40 | *6.67 | .0526 | 7,367 | 5,062 |
| | Anhydrite (residuum) | 700 | 2.7 | 2.52 | 2.45 | 4.6 | 1.86 | *7.04 | .3210 | 9,064 | 4,653 |
| | Halite | 715 | 2.7 | 2.16 | 2.11 | 3.2 | | | | | |
| | do | 720– 725 | 1.1 | 2.49 | 2.46 | 4.3 | | | | | |
| | do | 1,013–1,015 | 5.1 | 2.24 | 2.13 | 3.7 | | | | | |
| | do | 1,019–1,023 | 1.2 | 2.27 | 2.24 | 6.7 | | | | | |
| | do | 1,120–1,123 | 7.1 | 2.33 | 2.17 | 12.1 | | | | | |
| | do | 1,130 | 1.7 | 2.18 | 2.14 | 9.5 | | | | | |
| | do | 1,147–1,152 | .8 | 2.18 | 2.16 | 7.8 | | | | | |
| | do | 1,173–1,178 | 3.2 | 2.15 | 2.09 | 6.3 | | | | | |
| | do | 1,177–1,181 | 2.7 | 2.38 | 2.31 | 5.4 | | | | | |

TABLE 4.—*Physical properties of rock samples from Gnome shaft, as determined by static method*

[Analysts: T. C. Nichols, J. C. Thomas, and R. A. Speirer]

| Lab. No. P1– | Depth (ft) | Lithology of sample | Condition of sample | Description | Unconfined compressive strength (psi) | Secant Young's modulus (psi) | Secant range (psi) | Poisson's ratio | Shore hardness | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 102 | 320 | Anhydrite | Good | Lineation of gypsum-filled fractures approximately 70° to platens. Length, 3.0 in.; diameter, 1.470 in.; parallelism, .0012 in. Oven dried. | 3,900 | $2.86 \times 10^6$ | 500–1400 | 0.19 | 24 | Loading: Longitudinal strain, first cycle; latitudinal strain, second cycle. Failure occurred along fracture planes. |
| 104 | 343 | Gypsum | do | Both ends slightly chipped. No lineation. Length, 2.078 in.; diameter, 1.0 in.; parallelism, <.001 in. Oven dried. | 3,180 | $3.18 \times 10^5$ | 300–1300 | .10 | 12 | Loading: Longitudinal strain, first cycle; latitudinal strain, second cycle; compressive strength, third cycle. |
| 109a | 400 | Anhydrite and gypsum. | Fair | No fractures. One end of core chipped. Length, 2.716 in.; diameter, 1.438 in.; parallelism, .0009 in. Oven dried. | 2,400 | $2.2 \times 10^5$ | 500–1400 | .23 | | Loading: Longitudinal strain, first cycle; latitudinal strain, second cycle. |
| 109b | 400 | do | Poor | Many gypsum-filled fractures normal to platens. Length, 2.078 in.; diameter, 1.0 in.; parallelism, <.001 in. Oven dried. | 8,900 | $1.14 \times 10^6$ | 300–1600 | .10 | 7 | Loading: Longitudinal strain, first cycle; latitudinal strain, second cycle. Both extension and shear fractures occurred along gypsum planes during failure. |
| 112 | 515 | Dolomite | Good | A few weathered holes. No lineation. Length, 2.031 in.; diameter, 1.0 in.; parallelism, <.001 in. Oven dried. | 12,700 | $4.31 \times 10^6$ | 300–2500 | .27 | 17 | Loading: Longitudinal strain, first cycle; latitudinal strain, second cycle; compressive strength, third cycle. |
| 119 | 693 | Siltstone | Fair | Several fractures. One end chipped. No lineation. Length, 4.083 in.; diameter, 2.109 in.; parallelism, .0048 in. Oven dried. | 6,200 | $1.14 \times 10^6$ | 600–2300 | .31 | 13 | Only one cycle of loading. |
| 120 | 700 | Andydrite | Good | A small chip on one end. Lineation approximately parallel to platens. Length, 4.10 in.; diameter, 2.109 in.; parallelism, .0019 in. Oven dried. | 3,200 | $2.97 \times 10^6$ | 600–1700 | .42 | 19 | Only one cycle of loading. Failure occurred along planes normal to lineation. |

The hardness of the rocks (table 4) was measured on a Shore scleroscope. This instrument utilized a diamond-tipped hammer, which is raised to a standard height above the rock specimen and then dropped onto it. The height of the rebound is proportional to hardness and is recorded on a scale of 0 to 120.

Porosity of rocks above the salt ranges from as high as 34.7 percent for the Magenta Member of the Rustler Formation to as low as 1.1 percent for siltstone residuum at the top of the Salado Formation. Porosity of halite from the Salado ranges from 7.1 percent to 0.8 percent. Grain density ranges from 2.92 g per cc (grams per cubic centimeter) for the Magenta to 2.15 g per cc for the same siltstone residuum at the top of the Salado. Grain density of the halite ranges from 2.49 to 2.15 g per cc. Dry-bulk density ranges from a high of 2.49 g per cc in the Culebra Member of the Rustler Formation to a low of 1.81 g per cc in the Gatuna Formation. Dry-bulk density of the halite in the Salado ranges from 2.46 to 2.09 g per cc.

Sonic velocities were determined in the laboratory for rocks overlying the Salado Formation. Longitudinal velocities range from 15,205 fps (feet per second) for gypsum and anhydrite of the Tamarisk Member of

TABLE 5.—*Measured velocities aud calculated elastic moduli for rock salt near the position of the Gnome explosion*

[From Dickey (1964, p. b109). All arrival times determined from comparison of two or more records from each line of measurement except those for line *J–O*. Only one acceptable record was obtained from line *J–O*. Line *Y–Z*, the preexplosion line of measurement, is 5.5 feet higher stratigraphically than the other lines. Measurements by D. D. Dickey and D. R. Cunningham]

| Line of measurement (fig. 9) | Distance from explosion point (ft) | Length of line (ft) | Traveltime of first arrival (milliseconds) | | Velocity (fps) | | Poisson's ratio | Young's modulus ($10^6$ psi) | Shear modulus ($10^6$ psi) | Bulk modulus ($10^6$ psi) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Compressional | Shear | Compressional | Shear | | | | |
| | | | | | **Postshot measurements** | | | | | |
| *A–C* | 80–110 | 34.99 | 2.9 | 6.05 | 12,100 | 5,800 | 0.35 | 2.6 | 0.95 | 2.9 |
| *B–C* | 80–110 | 32.15 | 2.7 | 5.6 | 11,900 | 5,750 | .35 | 2.5 | .93 | 2.8 |
| *G–E* | 140–205 | 66.80 | 5.6 | 10.4 | 11,900 | 6,400 | .30 | 3.0 | 1.1 | 2.5 |
| *G–F* | 140–205 | 67.09 | 5.7 | 10.4 | 11,800 | 6,450 | .29 | 3.0 | 1.2 | 2.4 |
| *J–O* | 235–350 | 114.74 | 8.8 | 14.9 | 13,000 | 7,700 | .23 | 4.1 | 1.7 | 2.6 |
| *J–K* | 235–325 | 90.52 | 7.0 | 13.1 | 12,900 | 6,900 | .30 | 3.5 | 1.4 | 2.9 |
| *U–W* | 600–785 | 186.22 | 13.4 | 24.4 | 13,900 | 7,650 | .29 | 4.2 | 1.6 | 3.3 |
| | | | | | **Preshot measurements** | | | | | |
| *Y–Z* | 5–85 | 81.37 | 6.05 | 11.5 | 13,500 | 7,100 | .31 | 3.5 | 1.4 | 3.1 |

the Rustler Formation to 5,072 fps for sandstone of the Gatuna Formation. Transverse velocities range from 9,487 fps for the same gypsum and anhydrite sample to 3,244 fps for the Magenta Member of the Rustler.

### CHANGES IN PHYSICAL PROPERTIES

The dynamic properties of the rock salt in the underground workings at Project Gnome were calculated from preshot and postshot in situ measurements of the compressional and shear velocities of acoustic waves. This work was described by Dickey (1964). Figure 9 shows the plan of the preshot and postshot workings and location of the sonic-velocity stations. Velocities and calculated elastic moduli are shown in table 5.

Dickey (1964, p. B111) concluded that:

* * * the results of this study showed that (1) although fracturing of this rock is detectable by the acoustic method used, compaction is not, and (2) the elastic moduli are changed for reasons other than compaction. Furthermore, the amount of fracturing is semiquantitatively estimable by acoustic means. Compaction is not shown by the changes in elastic moduli caused by the explosion, because of the larger changes in elastic moduli not related to compaction. These changes, however, may indicate the amount and position of changes in stress of the rock surrounding an explosion.

Density changes were not detected in laboratory measurements (table 6), and, therefore, compaction was less than 1 percent on any sample tested.

TABLE 6.—*Physical properties of samples of halite from unit 10, Salado Formation*

[Analysts: John Moreland, Jr., and E. F. Monk. Salt-saturated kerosene density: 0.8098 at 19.8°C]

| Lab. No. P2– | Location in drift | Rock type | Effective porosity (percent) | Grain density | Dry-bulk density, mercury displacement | Saturated-bulk density (in salt-saturated kerosene) | Total porosity (percent) |
|---|---|---|---|---|---|---|---|
| 1198 | Sta. 6+94 | Preshot halite. | 1.0 | 2.17 | 2.14 | 2.15 | 1.2 |
| 1012 | 105 ft from shot-point. | Postshot halite. | 1.02 | 2.18 | 2.11 | .......... | 3.65 |
| 1199 | ....do.... | ....do...... | .9 | 2.18 | 2.14 | 2.15 | 1.7 |
| 1200 | ....do.... | Postshot vein halite. | .9 | 2.17 | 2.13 | 2.13 | 1.9 |

### MINOR ELEMENTS IN SALADO FORMATION IN THE GNOME DRIFT

The Gnome drift, whose rocks show a sequence of cyclic deposition, provided a rare opportunity to study the distribution and association of minor elements of evaporite rocks in a nonmineralized part of the Salado Formation.

Semiquantitative spectrograph analyses were made on samples from seven stratigraphic units exposed in the Gnome drift and from four replacement zones in these units. In addition, analyses for minor elements were made for comparative purposes on samples of the langbeinite and sylvite ore zones from the 800- and 900-foot levels of the International Minerals and Chemical Corp. mine, 12 miles northwest of the Gnome site, and on samples of selenite crystals precipitated in Salt Lake, 8 miles west of the site. These analyses were by Gard, Cooper, and others (1962, tables 9, 11). Samples from the Gnome drift are described in table 7 of the present report, and the semiquantitative spectrographic analyses of these samples are summarized in table 8.

Many elements either compose the clay minerals or are closely associated with the clays. These elements are, in order of decreasing abundance: potassium, magnesium, calcium, silica, aluminum, iron, titanium, lithium, boron, barium, manganese, vanadium, zirconium, chromium, molybdenum, copper, nickel, yttrium, gallium, cobalt, scandium and ytterbium. Several elements that are associated with the clays also form parts of one



TABLE 7.—*Description and stratigraphic position of samples of Salado Formation analyzed by semiquantitative spectrographic methods*

[All samples from Gnome drift]

| Sample | Stratigraphic unit within Salado Formation | Description |
|---|---|---|
| 30 | 10 (upper part) | Halite rock, colorless. |
| 31 | ....do....... | Halite rock, orange, translucent; contains trace of disseminated orange polyhalite. |
| 33 | ....do....... | Halite rock; composite sample. |
| 34 | 10 (lower part) | Halite rock; contains some polyhalite. |
| 35 | ....do....... | Halite rock; contains some gray clay and trace of polyhalite. |
| 37 | 11 | Halite rock; contains gray clay and streaks of polyhalite. |
| 39 | 12 | Halite rock; contains gray and brown clay. |
| 41 | 13 (upper part) | Halite rock, orange; shows streaks of orange polyhalite and brown clay; contains trace of gray clay. |
| 42 | ....do....... | Halite rock, colorless; contains some brown clay and trace of orange polyhalite. |
| 43 | 13 (lower part) | Halite rock; contains some brown clay and polyhalite. |
| 46 | 14 | Halite rock; contains blebs of orange polyhalite. |
| 47 | 15 (upper part) | Polyhalite rock, moderate-reddish-brown; contains trace of halite. |
| 48 | 15 (middle part) | Polyhalite rock, moderate-reddish-brown; contains trace of halite. |
| 49 | 15 (lower part) | Same; contains inclusions of gray clay. |
| 50 | 15 | Underclay, gray; contains some halite and trace of polyhalite. |
| 51 | 16 | Halite rock; 0.3- to 0.5-in.-square crystals; contains some gray clay and orange polyhalite. |
| 52 | 16 | Halite rock; 0.3- to 1.0-in.-square crystals; contains some brown clay. |
| 53 | 16 | Halite rock, colorless; contains some blebs of orange polyhalite. |

TABLE 8.—*Summary of semiquantitative spectrographic analyses of evaporite rocks (Salado Formation) from Gnome drift, in percent*

[Samples described in table 7. Analyst: J. C. Hamilton. M, major constituent (greater than 10 percent); L, looked for but not detected. Average: where results are reported as 0 or <, with a number, the half-value of the threshhold of detection was used in determining the average. Other elements looked for but not detected: phosphorus, silver, arsenic, gold, beryllium, bismuth, cadmium, germanium, hafnium, mercury, indium, lanthanum, nickel, palladium, platinum, rhenium, antimony, tin, tantalum, tellurium, thorium, thallium, uranium, tungsten, zinc, and cerium]

| Unit in Salado Formation | 10 | 11 | 12 | 13 | 14 | 15 | | 16 |
|---|---|---|---|---|---|---|---|---|
| Sample Nos | 30, 31, 33–35 | 37 | 39 | 41–43 | 46 | 47–49 | 50 | 51–53 |
| Si | 0.007 –0.15 | 0.3 | 1.5 | 0.3 –0.7 | 0.007 | 0.03 –0.3 | M | 0.003 –0.3 |
| Al | .015 – .15 | .3 | .7 | .3 | .007 | .015 – .3 | 1.5 | <.005 – .15 |
| Fe | .007 – .03 | .05 | .3 | .1 – .2 | .002 | .07 – .3 | .7 | 0 – .03 |
| Mg | .15 –2 | .7 | 3 | .7 –2 | .5 | 5 | 7 | .15 – .5 |
| Ca | .07 –7 | .5 | .07 | .07 –5 | 1.5 | M | .7 | .1 – .5 |
| Na | M | M | M | M | M | 1 | 7 | M |
| K | 0–5 | 1 | 1.5 | 0–5 | 2 | M | 7 | 0–1 |
| Ti | .0007– .003 | .005 | .03 | .01 – .015 | <.0005 | .0015– .015 | .15 | <.0005– .007 |
| Mn | 0– .0003 | .0007 | .005 | .001 – .0015 | L | .0005– .003 | .015 | 0– .0007 |
| B | L | L | .005 | L | L | L | .05 | L |
| Ba | <.0002– .0015 | .007 | .005 | .0005– .003 | <.0002 | .005 – .007 | .015 | <.0002– .0005 |
| Co | L | L | L | L | L | L | .0007 | L |
| Cr | 0– .0002 | .0005 | .002 | .0003– .0005 | L | 0– .005 | .005 | L |
| Cu | .0001– .001 | .0001 | .0002 | .0002– .0003 | .00015 | .0002– .0015 | .002 | 0– .0007 |
| Ga | L | L | L | L | L | L | .0015 | L |
| Li | L | L | .03 | L | L | L | .1 | L |
| Mo | L | L | L | L | L | L | .003 | L |
| Ni | L | L | L | L | L | L | .002 | L |
| Sc | L | L | L | L | L | L | .0007 | L |
| Sr | .003 – .3 | .05 | .005 | .005 – .3 | .07 | .15 – .3 | .015 | .005 – .05 |
| V | L | L | .002 | 0– .001 | L | .001 – .0015 | .007 | L |
| Y | L | L | L | L | L | L | .002 | L |
| Yb | L | L | L | L | L | L | .00015 | L |
| Zr | L | L | .0015 | L | L | L | .007 | L |

or more minerals. Potassium and magnesium form an integral part of the polyhalite lattice, and calcium is also a major constituent of polyhalite. Included iron, which is also concentrated in the clays, imparts the characteristic reddish-orange color to polyhalite. Barium is more abundant in the clay concentrates and in the sulfate mineral polyhalite than in the halite.

Boron is commonly associated with the clays but was not found in the halite or polyhalite. Strontium is relatively abundant in polyhalite but is less abundant in halite rocks containing accessory polyhalite as blebs, streaks, or disseminated particles.

Elements reported by Moore (1958b, tables 4, 5) in anhydrite, polyhalite, and halite rocks of the Salado Formation, but not determined by the semiquantitative spectrographic method, are: chlorine, sulfur, oxygen, hydrogen, bromine, carbon, fluorine, iodine, and selenium. Thorium and zinc were also reported by Moore but are not present in the Gnome samples in amounts detectable by this method. Six elements not previously reported were detected by the spectrographic method: chromium, lithium, scandium, yttrium, ytterbium, and gallium.

## MINERALOGY AND PETROGRAPHY OF THE SALADO FORMATION NEAR THE DEVICE CHAMBER

A petrographic study was made by B. M. Madsen of the evaporite rocks near the device chamber, and the insoluble clastic material from these rocks was studied by Julius Schlocker. Seventeen thin sections from a 100-foot section of the recovery-hole core and four thin sections from rock samples collected in the drift were studied and described. The 100-foot section of the core extended from 50 feet above to 50 feet below the device chamber. The predominant mineral is halite, and lesser amounts of polyhalite and clay are present. The other minerals present are magnesite, quartz, chlorite, mica, and anhydrite, which generally occur in amounts of 1 percent or less.

### HALITE

Halite makes up more than 90 percent of the 100-foot section of the recovery-hole core. The halite rock is hypidiomorphic-granular and shows no strain birefringence or schistosity in thin section. The grains range in size from 0.75 to 50.8 mm, but most are between 7.62 and 17.8 mm. A plot of the crystal size of the halite on a strip log showing lithology and depth shows a slight tendency for the size of the halite crystals to decrease as the disseminated-clay content increases. More than half the halite crystals contain negative crystals (crystal-shaped voids) filled with a liquid and gas. These negative crystals are both cubic and rectangular, but they always maintain right-angle corners, and they are as much as 0.05 mm in diameter. Generally the negative crystals occur in zones three or four crystals wide and parallel to the cleavage of the host halite crystal, but in some the zones of negative crystals are at a 45° angle to the cleavage. The negative crystals also occur as curving zones or in small irregular masses of several hundred crystals.

### POLYHALITE

The second most abundant mineral in the 100-foot section of core is polyhalite, which ranges in color from white and gray to brick red. In thin section the polyhalite exhibits a variety of textures, which are divided into four types (Schaller and Henderson, 1932, p. 51). These types may occur singly, intimately mixed, or grading from one to the other.

The first texture is fine grained, the crystal size ranging from 0.001 to 0.02 mm, and is allotriomorphic-granular. The fine-grained texture generally characterizes the more massive forms of polyhalite.

The second texture is coarse grained, the crystal size ranging from 0.02 to 0.5 mm. Crystals range from anhedral to euhedral, but are mainly subhedral and twinned.

The third texture is euhedral twinned and includes two distinct forms, both of which show laminar and sector twinning, are colorless, and range in crystal size from 0.2 to 6.0 mm. One form of the euhedral-twinned group is spear shaped (fig. 7*A*), and the length is no greater than twice the width. The second form of the euhedral-twinned variety is the lath (fig. 7*B*). The length of the euhedral-lath twins is generally at least 10 times the width; normally this form occurs as inclusions in halite crystals or as projections into a halite crystal. The lathlike crystals range in width from 0.01 to 0.5 mm and in length from 0.2 to 5.0 mm.

The fourth texture is fibrous and is characterized by crystals that range in width from 0.001 to 0.004 mm and in length from 0.1 to 0.9 mm. The fibrous and fine-grained granular textures are gradational and commonly occur together. Individual fibrous crystals are common in the halite. The fibrous form shows all gradations from almost perfect spherulites to faint wisps of fibers.

*Color.*—Polyhalite imparts a light-orange or reddish-brown color to the rock and is the most conspicuous megascopic mineral. The color depends on the amount of

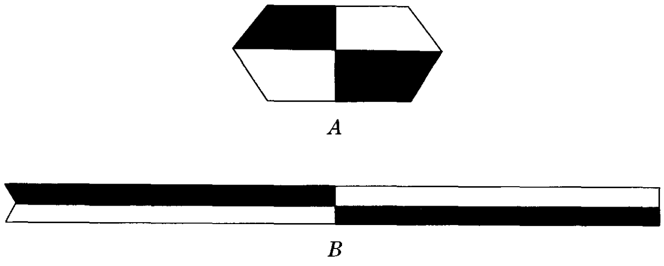



FIGURE 7.—Twinned polyhalite crystal forms: *A*, spear shaped; *B*, lath shaped.

included hematite in the polyhalite. Hematite occurs as an extremely fine dust disseminated through the fine-grained and fibrous forms of polyhalite but is absent in the euhedral forms, which are colorless. Hematite also occurs in the brown clay and along some cleavage planes in the halite immediately adjacent to the brown clay inclusions. Mottling observed at the top of the Union anhydrite, a locally used name, in the Salado Formation is due to a mixture of hematitic fine-grained to fibrous polyhalite and colorless coarse-grained polyhalite.

*Structure.*—Polyhalite occurs as blebs, growths, streaks, seams, beds, bands, and disseminated crystals or particles. The terms "bed," "band," and "seam" are applied to horizontal laminae of polyhalite which may be brick red, orange, or white and range in thickness in this part of the section from a few hundredths of a foot to 1.5 feet. In texture these laminae are mostly fine grained or fine grained to fibrous. At the contact of a polyhalite band with halite, long euhedral-twinned laths of polyhalite usually project into the halite. Rounded masses of coarse-grained polyhalite and remnants of large euhedral-twinned crystals of polyhalite are also present in some bands.

Polyhalite is nearly ubiquitous in the halite as small masses that make up 1–10 percent of the rock. Where these masses are roughly equidimensional, they are called blebs or growths; if they are at least three times longer than they are wide, they are called streaks. These small masses average 1–5 mm in width, are orange, and occur in or between halite crystals. Generally they have a center of fine-grained polyhalite, and long fibrous or euhedral laths make up an outer rim that projects into the surrounding halite, The laths projecting into the halite are so evenly developed that they look like the teeth of a comb or the spokes of a wheel. The centers of some blebs are mixtures of coarse- and fine-grained polyhalite or of fine-grained and fibrous polyhalite. A few blebs are composed of a mat of fibrous crystals and contain no fine-grained polyhalite.

### ANHYDRITE

Anhydrite was found in only two thin sections, where it amounted to 1 percent or less. One thin section is from a sample taken 1.5 feet below marker bed 121 and shows anhydrite crystals at least 5.5 mm long that have been badly corroded by halite. The other section is from a sample taken from the top of marker bed 120 and shows a single perfectly euhedral anhydrite crystal in halite. This crystal is 0.21 mm long and 0.07 mm wide.

### CLASTIC MATERIAL

The presence of clastic material in the Salado Formation is an anomaly. This material was probably not brought in from the open sea to the south, and a postulated landmass to the northwest must have been many miles away. The clastic material is mainly clay and silt size (table 9), has minor amounts of sand-sized material, and could have been carried in suspension by streams from such a landmass; possibly some of this material was airborne. According to Julius Schlocker (written commun., 1961), the sand-sized material consists of doubly terminated quartz crystals that attain a maximum diameter of 0.6 mm. Cores of some of these euhedral crystals show ghosts of well-rounded quartz grains, which indicate that the crystals were much smaller when deposited and that they acquired overgrowths of quartz after deposition. Clasts of other minerals, which are sparse and mostly very fine grained, include microcline, plagioclase (mostly oligoclase), and quartz with biotite inclusions.

TABLE 9.—*Approximate size and heavy-mineral composition of clastic material in units 11–13 of the Salado Formation in Gnome drift*

[Julius Schlocker, written commun., 1961]

| Unit | Percentage of material of given size | | | Heavy minerals (percent) |
|---|---|---|---|---|
| | Less than 2 microns | Silt | Sand | |
| 11 | 75.0 | 15.0 | 10.0 | 0.17 |
| 12 | 78.3 | 14.5 | 7.2 | .22 |
| 13 | 73.2 | 19.3 | 7.5 | .13 |

The heavy-mineral assemblage, according to Schlocker (written commun., 1961), is approximately the same in all units and is as follows.

*Abundant:* ilmenite; leucoxene; magnetite with drusy surfaces; biotite, green and brown; muscovite.

*Common:* hornblende, blue-green to yellow-green, pale-brown to brown, green to brown; monazite; epidote; chlorite; tourmaline, yellowish-red-brown to colorless, greenish-brown to colorless, dark-green to pale-brown.

*Scarce:* zircon; rutile; apatite; sphene; clinozoisite; garnet, pale-brown, colorless, and rutilated; iron sulfides.

*Rare:* oxyhornblende; anatase; anhydrite; actinolite-tremolite; sillimanite in quartz; hypersthene, etched.

*Clay.*—The term "clay" is here used for the water-insoluble minerals of clay and silt size. Clay-sized particles make up more than 75 percent of this material. This clay-silt mixture occurs as irregular streaks, inclusions, and partings in the Salado Formation. The partings vary in thickness from a featheredge to 19 mm. The silt-sized material was examined with the petrographic microscope, and the clay-sized fraction was analyzed by X-ray diffraction by Julius Schlocker of the Geological Survey.

The silt-sized material is made up largely of quartz, magnesite, chlorite, and mica. All clay-sized samples that were examined are of similar composition, according to Schlocker (written commun., 1962), and contain about equal proportions of (1) interstratified chlorite and montmorillonite having both regular 1:1 alternations and random alternations; (2) mica, both trioctahedral (biotite: phlogopite type) and dioctahedral (muscovite type); and (3) chlorite. A trace of magnesite is present in the clay-sized material. In the halite rock the proportion of clay- and silt-sized grains ranges from 0 to 40 percent, but averages 1–3 percent. Talc, which commonly occurs in halite rock, was not found. The color of the clay ranges from gray to gray green to reddish brown. The reason for the color difference was not determined. The colors persist even in the less than 2-micron-sized fraction and in the clay minerals themselves.

## EFFECTS OF THE NUCLEAR EXPLOSION

The Gnome shot was fired at noon on December 10, 1961, and produced a yield of about 3 kilotons (equivalent to 3,000 tons TNT). At shot time the ground surface above the detonation point rose about 5 feet and then dropped (Hoy and Foose, 1962). Shortly thereafter, observers 5 miles away felt a strong ground roll.

The ground surface was permanently domed upward for more than 400 feet radially around ground zero, the maximum rise being 1.9 feet. An irregular pattern of radial and concentric fractures with slight displacement was formed in the stabilized caliche pad and adjacent dune sand. Most of the concentric fractures had the outer side upthrown (Hoy and Foose, 1962).

One interesting surface effect was the appearance shortly after the shot of a large number of freshly dug or recently cleaned-out animal burrows in the vicinity of ground zero (Hoy and Foose, 1962).

The explosion melted approximately $3.2\times10^6$ kilograms of salt and produced a standing cavity with a volume of about 27,200 cubic meters (Rawson and others, 1965). The shock of the explosion opened radial fractures and produced some thrust faults in the adjacent rock that were filled with melted salt and rock fragments. Fractures as much as 130 feet from the cavity were injected with radioactive gases, as shown by blue coloration of the salt.

A few moments after firing, the shot vented into the drift and up the shaft, having breached the salt in the vicinity of the line-of-sight neutron-tube hole and having blown a rupture disk out of a ventilation hole in the blast door. Stemming at the bypass section near the blast door prevented any ultrahigh-pressure gases or particles from escaping through the vent. For more than a day clouds of steam laden with short-lived radioactive gases drifted gently from the shaft and ventilation pipes. Air and surface contamination were closely monitored, and traffic near the site was stopped for a short time to ensure public safety. Because of the radiation, reentry to the main station was delayed for nearly a week.

The shot was completely contained by the rocks directly over the shot, and there has been no indication that any radioactivity leaked into the ground water in the Culebra Dolomite Member of the Rustler Formation.

### EFFECT ON THE SHAFT

Damage to the shaft was very limited. At 75 feet and 90 feet below the collar, the reinforced-concrete shaft lining displayed horizontal fractures, with minor lateral movement, around its entire circumference. The concrete liner above each fracture had moved radially away from ground zero relative to the part below. Neither fracture had a displacement of more than one-fourth inch. The differential movement at these two positions was probably localized by two contacts: at 90 feet by the contact of the Dewey Lake Redbeds with the less consolidated overlying Gatuna Formation, and at 75 feet by a contact between conglomerate and less consolidated sandstone in the Gatuna.

The concrete lining contained several minor horizontal fractures, with showed no visible displacement, at depths of 160 and 480 feet. The lower of these, about 15 feet above the top of the water-bearing Culebra Dolomite Member, produced a slight water seep. However, no large amount of water seeped from the Culebra into the shaft or the cavity (J. B. Cooper, U.S. Geol. Survey, oral commun., 1962). Below the concrete lining there was small-scale spalling of salt and clayey beds from the shaft wall.

### EFFECT AT THE MAIN STATION

At the main station (junction of the shaft and drift) damage from the shot consisted of large-scale spalling from the ribs, especially at exterior corners, and of slabbing from the back of about 3–4 feet of units 13 and 14, which parted at the contact with the clayey units 11 and 12. Where roof bolts, netting, and a monorail were affixed in the back, large slabs of units 13 and 14 were hanging free, and this loose rock had to be removed during cleanup operations.

The marker bed 121 polyhalite (unit 15) was bleached to a depth of a few millimeters, probably by the steam that leaked from the cavity. The 16-foot-deep sump at the bottom of the shaft was filled with water condensed from the steam, and, for a few weeks after the explosion, ankle-deep water was present on the sill (floor) at the main station.

### THE REENTRY DRIFT

Because radiation levels were high in the original drift, a reentry drift was driven parallel to and about 30 feet south of the original drift. The reentry drift was constructed to allow close-in sample-recovery drilling and recovery of instruments buried before the shot.

The reentry drift and appurtenant exploratory laterals were mapped in June 1962, 6 months after the shot was fired (pl. 2). Unlike the original drift, which was horizontal, the reentry drift was sloped slightly downward, following the bedding, to take advantage of the parting between beds 11 and 12. This provided a smooth strong back which did not require any bolting. The reentry drift, thus, exposed the same beds for its entire length.

*Seeps.*—Explosion effects, such as faults, fractures, and irradiated salt, were not seen in the reentry drift beyond 250 feet from the shotpoint. The most obvious difference observed between the salt exposed in the reentry drift and that exposed in the preshot drift was the presence of water seeps along the reentry drift. Several seeps were visible at the base of unit 15 (from the clay underlying the polyhalite) and from the thin clayey units 11 and 12. This water must have been derived from the steam created by the blast. If it had merely been moisture squeezed out of the clays by the blast, it would have been more widely distributed and should have been more abundant where the clays were thicker. Seeps also were associated with the grout-filled instrument holes intercepted by the drift. Some of this water could have been introduced by the grouting operation.

### VENTING

Venting occurred because the larger-than-anticipated cavity and spalling from the cavity walls resulting from the explosion reduced the separation between the cavity and the end of the straight part of the drift. Radial fracturing from the cavity provided avenues of escape for the high-pressure steam, and, once open, these fractures became enlarged by solution and erosion. Salt along the path of the steam was dissolved and sculptured in potholelike cusps (fig. 8). At the drift elevation, the thin, potentially weaker, clayey halite beds—units 11 and 12—probably contributed by providing a lubricated zone of weakness.

### THE CAVITY

An open cavity about 70 feet high and more than 150 feet across resulted from the detonation and postshot collapse (fig. 5). In plan, the cavity is roughly oval and is elongated in the same direction as the drift (fig. 9). Postshot drilling indicated that strata 200 feet above the shotpoint were permanently displaced 5 feet

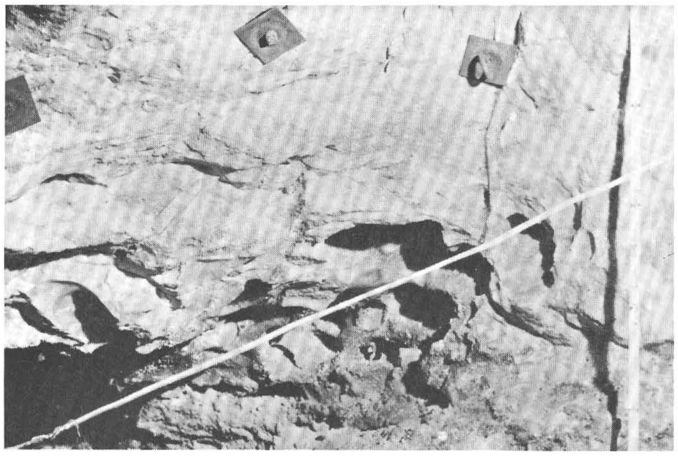


FIGURE 8.—Steam-eroded potholes in unit 10 where shot vented into preshot drift. Corner of preshot drift shows at lower left.

upward (Lawrence Radiation Lab., written commun., 1962), and that the Union anhydrite, a locally used name, in the Salado Formation, which lay 55 feet below the shotpoint, was displaced downward more than 10 feet (T. S. Sterrett, U.S. Geol. Survey, oral commun., 1962).

The bottom of the cavity contains a heap of rubble composed of large angular blocks of salt which have fallen from the vault and sides (frontispiece). Bowed-up ends of strata crop out in the walls of the cavity, and the walls exhibit no evidence of melting. Colors in the cavity are spectacular and include red, brown, white, orange, yellow, and blue. The yellow and blue colors are caused by radiation damage to the salt. Radial fractures are seen in the vault of the cavity; these fractures narrow radially from the center of the vault. They are filled with white salt evidently redeposited from solution, and thin white salt stalactites hang from the vault and sides (frontispiece).

## EXPLOSION-INDUCED STRUCTURE

Detailed geologic mapping of the reentry drift disclosed that the detonation had surprisingly little effect on the strata lying at the same altitude as the shotpoint. Evidence for this is, of course, confined to what could be seen in the limited postshot mine workings. Undoubtedly, blast effects will be found in salt beds above and below the drift level if exploration is carried out at other levels. A belt of salt about 30 feet high in the cavity wall at about device level seems to have been moved radially outward as a unit, and the beds above it are bent upward. The contact between beds showing these different types of movement lies about at marker bed 119 (detailed measured section, p. 24), and it is postulated, therefore, that structures similar to those exposed in the postshot workings will be found at least to that level. Beds logged in the recovery hole and shaft can be identified clearly in the cavity walls.

Major lateral blast-induced effects were largely confined to a radial distance of about 140 feet from the shotpoint, although curving vertical faults, concave toward the preshot drift and showing slight horizontal movement, are found as far as 250 feet away from the

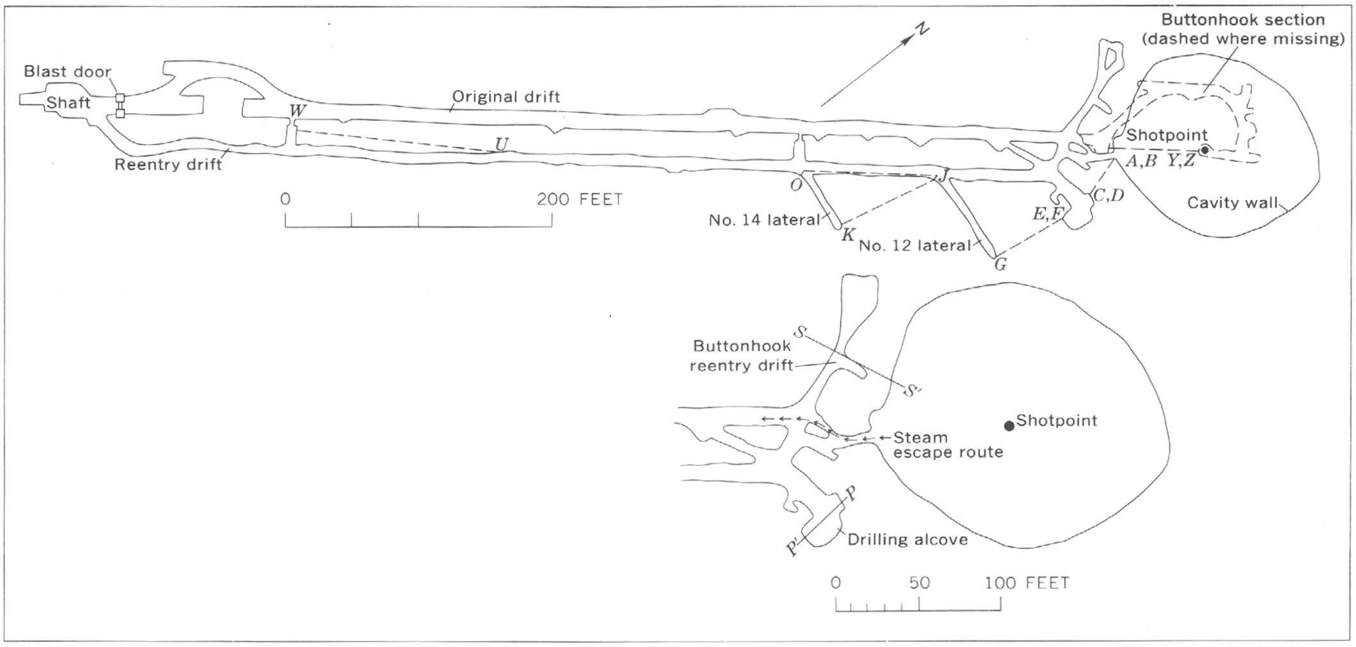



FIGURE 9.—Map of underground workings and cavity. Sonic velocity stations are indicated by italic letters, and lines of sonic measurement, by dashed lines; from Dickey (1964). Enlargement shows location of geologic cross sections (figs. 10, 12). Arrows show route of venting.

shotpoint. These faults probably were formed because of the relief effect of the preshot drift, although they may be tear faults representing the ends of thrust faults that lie concealed above the mine workings.

The contact between the thin clayey halite beds that form units 11 and 12 forms the back of the reentry drift. In many places the bottom of unit 11 displays the cast of ripple marks that were present on the upper surface of unit 12. These ripple marks were destroyed by differential movement along this contact and are commonly replaced by slickensides to about 230 feet from the shotpoint. Beyond there the ripple marks are intact. In most places the slickensides trend N. 35° E., roughly radically from the shotpoint; but at station 8+58, near the junction of the reentry drift and the lateral IH–8, a set of slickensides trends N. 80° E., indicating that some motion was not radial.

### STRUCTURE IN CONFINED SALT

Except for the radial fractures seen in the vault of the cavity and a few others exposed in the buttonhook reentry drift, blast-produced faults in the confined salt appear to be restricted to a 10-foot section of salt (units 13–15) bounded above by the clayey layers (units 11 and 12) and below by the clay at the base of the polyhalite. These fractures are mainly thrust faults that dip both toward and away from the cavity and die out in the clay layers. Overthrusts are more common than underthrusts. The thrust faults end laterally by curving downward into vertical tear faults that die out in the salt beds.

Typical examples of these faults are seen in the drilling alcove (section *A–A′*, pl. 2) where two thrust faults that dip toward the cavity are well exposed. The one exposed in the east wall has 2 feet of throw, which can be measured from the offset of the contact between units 13 and 14 in the alcove wall. A 2-foot-square hole dug in the wall revealed that, although unit 15 is offset, the fault dies out in the underclay and does not offset unit 16. The north end of this fault dies out in a tear fault in unit 13. The other fault has only one-half foot of throw and can be traced in the south, west, and north walls of the alcove. The lower end of the fault originates in the clay under unit 15 and offsets the polyhalite slightly, but the upper end is not exposed (fig. 11*A*). Figure 10 is an interpretation of these two faults.

In the No. 12 lateral, which was driven to recover an instrument, unit 14 displays horizontal hairline fractures along the wall nearest the cavity that are similar in appearance to the fault just described. The offset on these fractures could not be determined, nor is the direction of dip known, but any movement along them must have been very slight. The gouge in these fractures

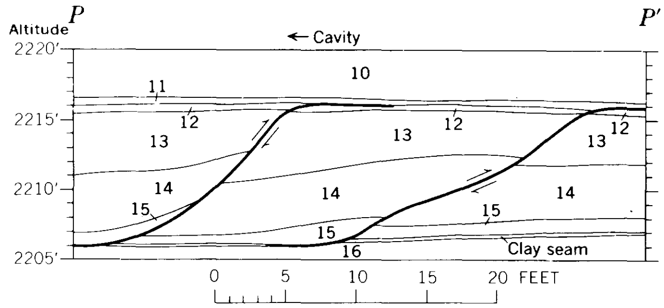



FIGURE 10.—Geologic cross section *P–P′* of drilling alcove, showing thrust faults. Right fault shown in figure 11*A*. See table 2 for description of numbered stratigraphic units.

is blue in places, indicating that radiation leaked this far along the fractures. There is no indication in this lateral of any offset of the polyhalite bed.

Adjacent to the cavity, faulting is more common and more complex, although no faults were seen that had more than a few feet of displacement. On many faults at least some component of movement could be measured, from offset either of beds or of mudcracks in unit 13.

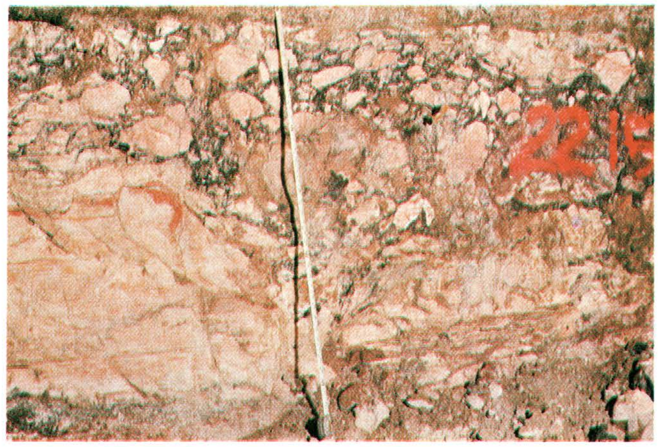
According to a resurvey of grout-filled instrument holes, total lateral displacement 100 feet from the shotpoint was 16 feet. An instrument 127 feet from the shotpoint had been moved away 8 feet. Bags of salt in the alcove at the end of the straight section of the preshot drift that initially were about 90 feet from the shotpoint were about 120 feet away and had been lithified into well-compacted salt breccia (fig. 11*B*). Outlines of individual bags with cloth fragments between are still discernible.

### STRUCTURE IN UNCONFINED SALT

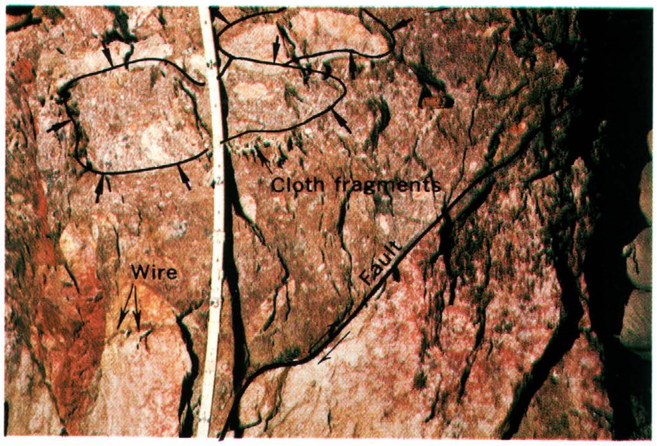
On the west side of the shotpoint, the buttonhook drift remained open up to shot time. It was designed to be blown shut when the shot went off, and in this it was eminently successful—material that had been left in the open drift was blown 35 feet from its original position and sealed tightly in a well-lithified intrusive breccia of salt. Complex thrust faulting accompanied by intrusive breccia is found as far as 110 feet from the shotpoint on this side of the cavity.

*Faulting.*—The rocks observed in the buttonhook reentry drift were complexly faulted. Several thrust faults can be seen along the right rib, and many of them contain melt. The section exposed in the left rib is unfaulted, but the beds lie about 4 feet above their preshot altitude. The thrust faults generally die out laterally in downcurving tear faults. The main rock unit involved in the faulting is unit 10, which has been thrust under itself. A small lateral driven toward the cavity revealed details of one of these faults (figs. 11*C*, 12).

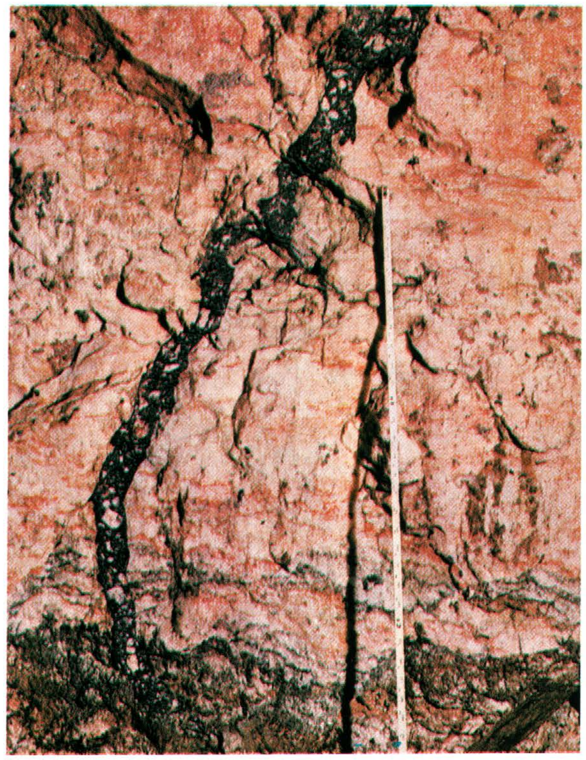
*A*



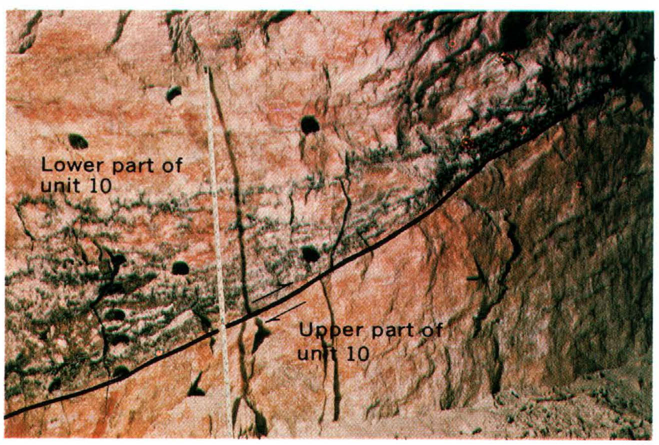
*D*




*B*



*E*




*C*

FIGURE 11.—Thrust faults, lithification, and brecciation resulting from the Gnome explosion. *A*, Thrust fault offsetting unit 15 (polyhalite) in drilling alcove. Fault originates in thin clay at base of polyhalite (left of hammer) and does not offset unit 16 (below hammer). *B*, Lithified salt bags. Note outline of bag shape top center indicated by arrows and cloth fragments near "2" on rule. (See pl. 2, section *B–B′*, left rib.) *C*, Underthrust fault in unit 10 in buttonhook reentry drift. Fault parallels bedding of lower plate, following a thin clay seam that normally lies 5.5 feet above basal clayey halite at left. Cavity to right. Scale is 3 feet long. (See pl. 2, section *E–E′*, left rib.) *D*, Intrusive breccia in buttonhook recovery drift. Blocks are composed of intensely granulated halite crystals, mainly from unit 10. Black matrix is chilled salt melt containing disseminated opaque black carbon and the blast-produced minerals laurionite and galena. (See pl. 2, section *D–D′*.) *E*, Intrusive breccia vein in rib of buttonhook recovery drift. Rule is 30 inches long. (See pl. 2, section *D–D′*.)

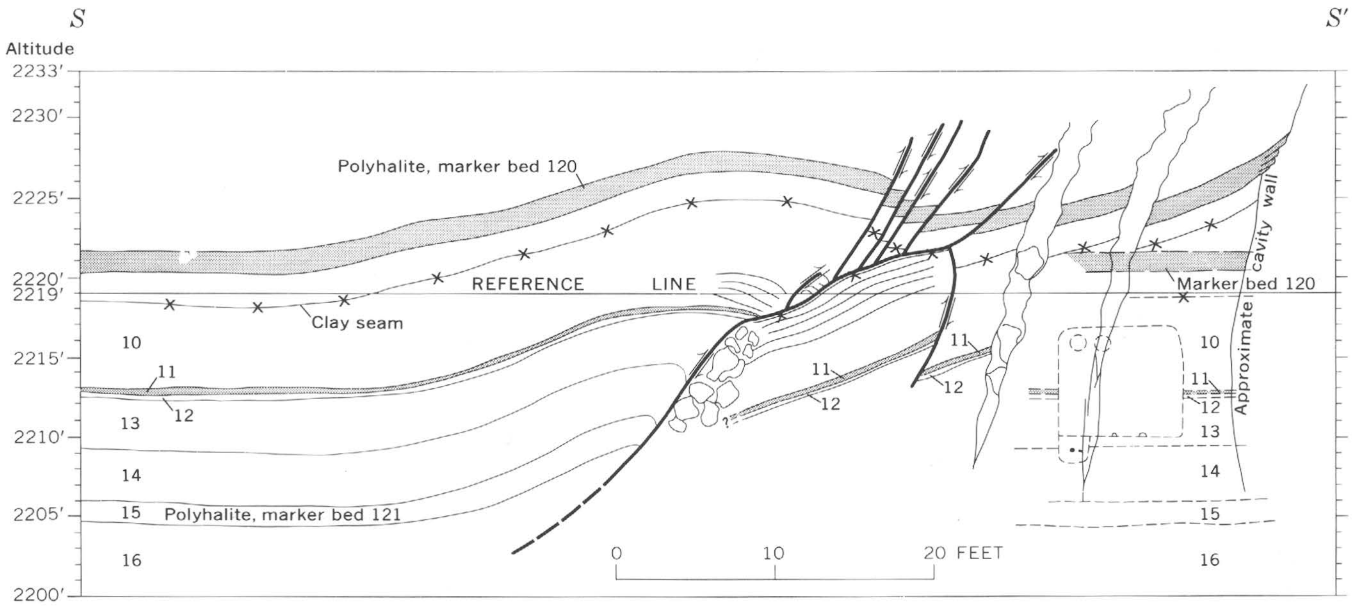



**FIGURE 12.**—Geologic cross section *S–S'* through buttonhook reentry drift. See table 2 for description of numbered stratigraphic units. Dashed lines indicate original position of buttonhook drift and strata.

The determination of the details of the structure from the limited exposures available was facilitated by the presence of several thin distinctive beds in unit 10.

*Intrusive breccia.*—Intrusive breccia is associated with the faulting along the right rib of the buttonhook reentry drift. The breccia consists of fragments that are largely composed of salt from unit 10 and range in diameter from a few millimeters to several tens of feet. These brecciated salt fragments occur in a matrix of black salt melt (fig. 11*D*). The black color is imparted by two blast-produced lead minerals—laurionite and galena—and disseminated carbon. The breccia contains twisted fragments of mine rail, steel ventilation pipe, wire, aluminum conduit, and cable covering and a few slightly scorched fragments of wood that had been left in the buttonhook drift. These fragments now lie about 35 feet from their original position. Salt in the blocks was granulated by the shock but not melted. Halite crystals in unit 10 ranged from 10 to 20 mm in diameter before the shot (fig. 13) but were shattered by the explosion and reduced to angular fragments measuring a millimeter or less (fig. 14*A*). This granulation must have resulted from the amount of free movement in these blocks, because it is not seen elsewhere, even in the cavity walls. Halite crystals in the cavity walls are fractured, but their outlines are plainly visible. Bedding planes in the larger fault blocks are distinct and still roughly horizontal, although the smaller blocks in the breccia are randomly oriented. Bedding planes are not disrupted within the larger blocks, although they may display drag against faults.

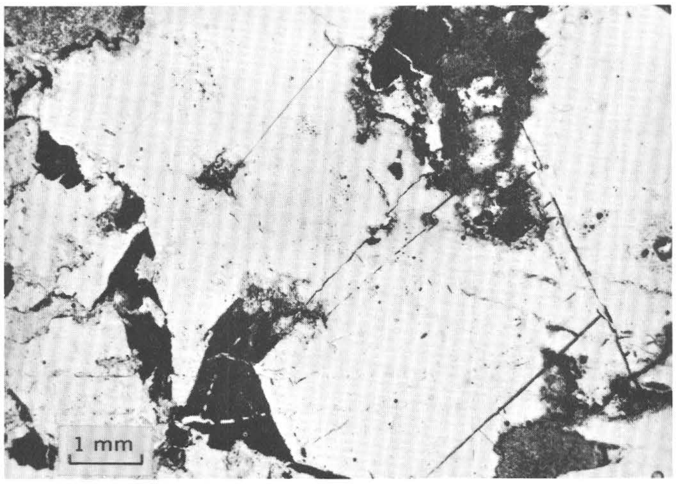
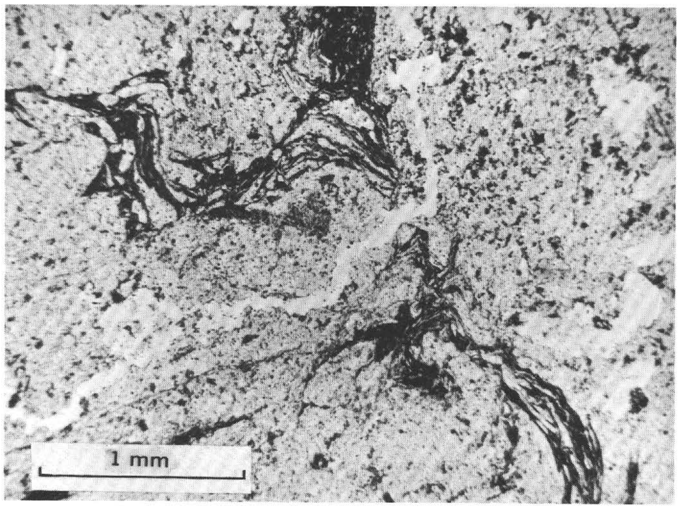



**FIGURE 13.**—Photomicrograph of preshot salt. Dark areas are polyhalite and clay. Note cleavage planes.

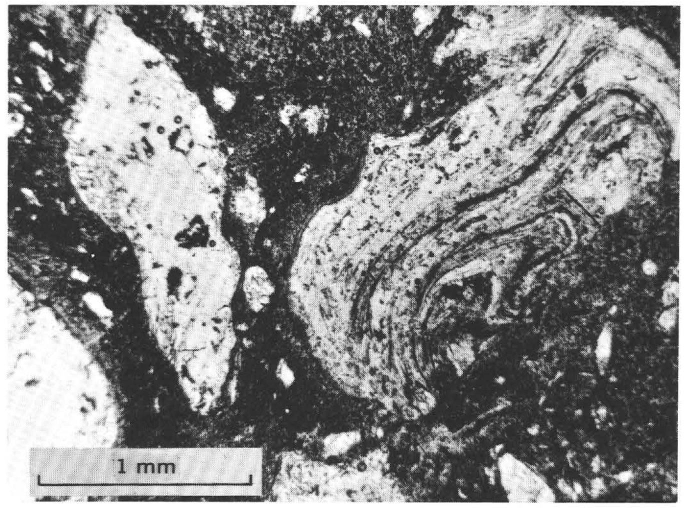
The density and porosity of samples of the granulated halite from the breccia and some of the vein material were determined in the laboratory (table 6) and compared with the results obtained on preshot sample (tables 3, 4). If any change in the density occurred, it was less than the limit of error due to sampling a slightly variable unit. Total porosity appears to have increased slightly, probably owing to the increased number of grain boundaries.

## NEW MINERALS FORMED

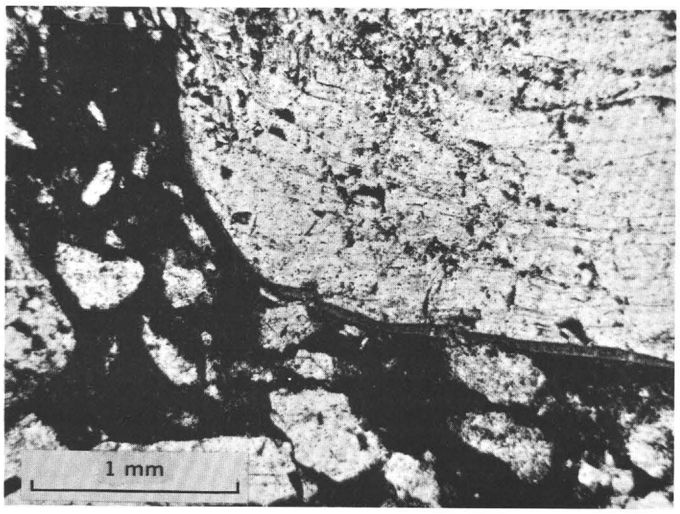
Associated with the blocks of granulated salt are black veins of intrusive breccia containing the manmade




A




B




C

FIGURE 14.—Photomicrographs of intrusive breccia resulting from Gnome explosion. *A*, Swirl pattern of fragments in intrusive breccia veinlet; black areas are carbon, laurionite, and galena. *B*, Plastically deformed salt fragment in intrusive breccia. *C*, Chilled border of melt against fragment; chilled border contains fewer opaque minerals.

minerals laurionite[1] and galena (Gard, 1963). These veins are not radioactive. The veins, which are seldom more than a few inches wide and are generally radial to the shotpoint (figs. 11*E*, 15), display sharp contacts with the host rock and are intruded along faults and fractures. The black veins and breccia matrix consist of melted and recrystallized salt and contain minute opaque black minerals disseminated between the salt crystals and sharp-bordered fragments of clear unmelted plastically deformed salt. Some of the unmelted salt fragments have a very thin selvage suggesting partial melting, and many of the fragments show warping and bending of bedding and cleavage suggesting plastic deformation (fig. 14*B*). In one thin section a tiny vein displays flow textures with warping and swirling of fragments reminiscent of that commonly seen in welded tuffs (fig. 14*A*). Minute fragments of copper and steel wire are not uncommon constituents.

Thin sections of the veins show that the melt has narrow chilled borders where it is in contact with many of the larger fragments and wallrock. The chilled borders are relatively free of lead minerals, but those minerals occur in the interior of the veins in the form of dust lying between the tiny crystals of melted salt (fig. 14*C*).

A mixed grab sample of black salt that was thought to be representative of the melt was collected from several places along the buttonhook recovery drift and submitted to the laboratory for analyses. Theodore Botinelly (written commun., 1962) reported as follows:

> A part of the sample was leached with distilled water in the ultrasonic agitator. The X-ray diffractometer pattern of the black (dark blue-gray) residue showed laurionite ($Pb(OH)Cl$), galena ($PbS$), and a mica. One fragment of vein material was cleaned of salt and leached with water. The residue amounted to approximately 15 percent of the weight of the original material. Slight effervescence with acid indicates some carbonate is present. (Magnesite is present in the preshot clays.) Microscopic examination showed, in addition, doubly terminated quartz crystals with a small 2V. Quartz from a preshot sample of fairly pure salt showed no 2V. Also present in the residue from the preshot salt were flakes of muscovite.
>
> Synthetic laurionite was prepared from lead acetate and sodium chloride solutions. Dehydrated at 150°C. for 12 hours it broke down to a mixture of lead oxides and lead chlorides. The mixture did not revert to laurionite in 48 hours. After 64 hours

[1] Laurionite was first found at Laurium, Greece, where it is formed by the action of sea water on slags from lead mines that were operated during the time of Pericles (4th century B.C.).

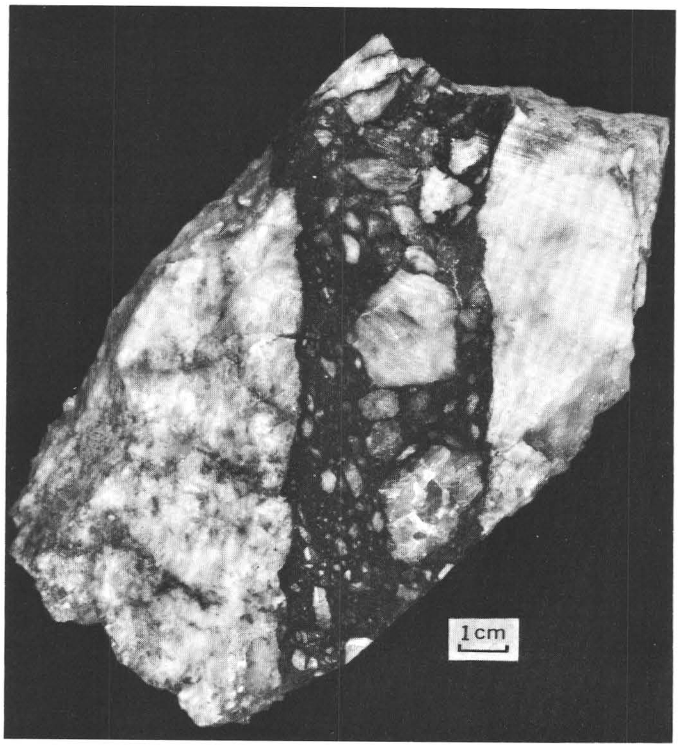



FIGURE 15.—Hand specimen showing vein of intrusive breccia. Unmelted salt fragments set in matrix of black melted salt. Black color is caused by presence of carbon and of lead minerals laurionite and galena, which were formed by heat and pressure of the shot.

in an atmosphere saturated with water, the mixture showed a laurionite X-ray pattern.

Induction-furnace determinations, by I. C. Frost, showed total carbon content of the insoluble residue of two samples to be 5.64 and 6.74 percent.

## ELEMENTS INTRODUCED

Comparison of the semiquantitative spectrographic analysis of the insoluble residue from the black veins (table 10) with analyses of the rock units exposed in the preshot drift (table 8) shows that silver, bismuth, lead, tin, zinc, and carbon are new elements that must have been introduced by the explosion. There are two potential sources for these elements: first, the nuclear device and material placed around the device, and, second, material left in the buttonhook drift after excavation.

At the time of the explosion, large quantities of lead, iron, and paraffin were present in the shielding block used in the device-performance measurements. Substantial amounts of wood and aluminum also were present.

The postshot presence of silver, bismuth, and zinc, which were not detected in preshot samples, is readily accounted for, as they are common minor impurities in

TABLE 10.—*Semiquantitative spectrographic analysis of insoluble residue of vein material resulting from the Gnome explosion*

[Asterisk indicates slight increase or decrease from amount present in preshot samples (table 8), probably due to analytical error. M, major constituent (greater than 10 percent)]

| Element | Percent | Element | Percent |
|---|---|---|---|
| Si | M | Cr | 0.005 |
| Al | 1.5 | Cu | .7 |
| Fe | 1.5 | Ga | .0015 |
| Mg | M | Li | *0 |
| Ca | .5 | Mo | *0 |
| Na | *1.5 | Ni | .007 |
| K | *1.0 | Pb | M |
| Ti | .15 | Sc | .0005 |
| Mn | .015 | Sn | .007 |
| Ag | .003 | Sr | .01 |
| B | .05 | V | *.005 |
| Ba | .01 | Y | .002 |
| Bi | .005 | Yb | *.0002 |
| Ce | 0 | Zn | .07 |
| Co | *.002 | Zr | .0007 |

lead from western smelters. The additional copper could have come either from the vicinity of the device or from a wire fragment left in the buttonhook drift that was unnoticed in the sample. The presence of zinc is harder to explain, but both the zinc and the copper could have been derived from brass fittings around the device. Carbon could have come from vaporized paraffin or wood near the device.

Rawson (1963, p. 133) suggested that the lead was derived from a small number of lead bricks that were placed at one point in the buttonhook drift, and that the carbon was derived from the burning of wood left in the buttonhook drift. Yet it hardly seems possible that the small amount of lead left in the buttonhook drift could have had such wide circumferential distribution from a point source. Wood fragments recovered from the breccia were only slightly scorched—not charred—and much of the wire found in the breccia still had uncharred insulation around it. Bags of salt that were only 90 feet from the shotpoint were found with fragments of the cloth still intact (fig. 11*B*), and the cloth showed no evidence of charring. Because of the foregoing evidence, it seems unlikely that materials left in the buttonhook drift could have been the source of the lead and carbon.

There are two possible sources for the melted salt in the vein material. The first of these, of course, is salt directly melted by the heat from the blast. The second is salt produced by shock-induced melting from the free-moving salt near the buttonhook drift. The first source seems more plausible because of the presence of elements that must have come from the device chamber. Moreover, the fact that the lead combined with sulfur and chlorine suggests that those elements were provided by vaporized halite and polyhalite near the device, and, as noted above, the organic materials in the breccia do not appear to have been subjected to heat intense enough to destroy them.

It is postulated, therefore, that the melted salt, as well as the introduced elements, was derived from the vicinity of the device and was injected through fractures that were sealed before any radioactive elements were able to escape. There was no increase in iron content in the postshot rocks. Presumably the iron did not vaporize as early as the other elements [2] and thus was unable to escape.

The lead combined with chlorine from the sodium chloride and with water to form laurionite and with sulfur derived from the sulfate mineral polyhalite to form galena. The presence of the OH radical in the laurionite suggests that the mineral was formed at a temperature less than 142°C, because above that point laurionite breaks down into lead chlorides and lead oxides. Thus, it must have formed approximately in place during retrograde temperature change.

## DETAILED DESCRIPTION OF ROCKS IN THE GNOME SHAFT

Section measured in 1961 (preexplosion) by L. M. Gard, Jr., and W. A. Mourant. Color designations are from the Rock-Color Chart (Goddard and others, 1948)

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Concrete collar | 0.8 | 0.0 – 0.8 |
| Fill (caliche material used to stabilize area) | .5 | .8 – 1.3 |
| Alluvial bolson deposits (Quaternary): | | |
| Sand, moderate-brown (5*YR* 4.5/5), unconsolidated (dune sand); made up of fine to medium subrounded to well-rounded clear and dark-stained quartz grains; contains some quartz crystals with subrounded faces | 7.6 | 1.3 – 8.9 |
| Caliche, white, poorly indurated; contains white calcium carbonate cementing sand like that described above | 3.3 | 8.9 – 12.2 |
| Sand, moderate-brown (5*YR* 4.5/5), unconsolidated; made up of fine to coarse subrounded to well-rounded clear and stained quartz grains; some quartz crystals have subrounded faces; contains some small grains of calcareous cementing material | 30.8 | 12.2 – 43.0 |
| Total thickness of alluvial bolson deposits | 43.0 | |
| Gatuna Formation (Pleistocene(?)): | | |
| Sandstone, moderate-brown (5*YR* 4.5/5), very fine grained to medium-grained with pebbles as large as 4 mm, partly indurated; made up of subrounded to well-rounded clear and dark-stained quartz grains; has calcareous cement | 2.0 | 43.0 – 45.0 |
| Conglomerate, pale-red (10*R* 6/2), well-indurated; made up of 20 percent fine to medium sand, 50 percent coarse-grained sand, 30 percent very fine to coarse pebbles of quartzite, limestone, siltstone; has calcareous cement | 1.0 | 45.0 – 46.0 |
| Sandstone, as in 43.0–45.0 ft; contains thin lenses of conglomerate as above | 1.7 | 46.0 – 47.7 |
| Conglomerate, as in 45.0–46.0 ft | .5 | 47.7 – 48.2 |
| Sandstone, as in 43.0–45.0 ft | .4 | 48.2 – 48.6 |
| Conglomerate, as in 45.0–46.0 ft | 1.3 | 48.6 – 49.9 |
| Sandstone, as in 43.0–45.0 ft | .6 | 49.9 – 50.5 |
| Conglomerate, as in 45.0–46.0 ft | .4 | 50.5 – 50.9 |
| Sandstone, as in 43.0–45.0 ft; contains three lenses (each about 0.05 ft thick) of conglomerate as in 45.0–46.0 ft | 2.6 | 50.9 – 53.5 |
| Conglomerate, as in 45.0–46.0 ft | .6 | 53.5 – 54.1 |
| Sandstone, as in 43.0–45.0 ft | .6 | 54.1 – 54.7 |
| Conglomerate, as in 45.0–46.0 ft | .1 | 54.7 – 54.8 |
| Sandstone, as in 43.0–45.0 ft | .2 | 54.8 – 55.0 |
| Conglomerate, as in 45.0–46.0 ft | .5 | 55.0 – 55.5 |
| Sandstone, as in 43.0–45.0 ft | .3 | 55.5 – 55.8 |
| Conglomerate, as in 45.0–46.0 ft | 2.4 | 55.8 – 58.2 |
| Sandstone, as in 43.0–45.0 ft | 2.3 | 58.2 – 60.5 |
| Conglomerate, as in 45.0–46.0 ft | .8 | 60.5 – 61.3 |
| Sandstone, as in 43.0–45.0 ft | 2.3 | 61.3 – 63.6 |
| Conglomerate, as in 45.0–46.0 ft | .1 | 63.6 – 63.7 |
| Sandstone, as in 43.0–45.0 ft | 1.8 | 63.7 – 65.5 |
| Conglomerate, as in 45.0–46.0 ft | .2 | 65.5 – 65.7 |
| Sandstone, as in 43.0–45.0 ft | .6 | 65.7 – 66.3 |
| Conglomerate, as in 45.0–46.0 ft | 1.8 | 66.3 – 68.1 |
| Sandstone, as in 43.0–45.0 ft | .7 | 68.1 – 68.8 |
| Conglomerate, as in 45.0–46.0 ft | .2 | 68.8 – 69.0 |
| Sandstone, as in 43.0–45.0 ft | 3.1 | 69.0 – 72.1 |
| Conglomerate, as in 45.0–46.0 ft | .1 | 72.1 – 72.2 |
| Sandstone, as in 43.0–45.0 ft | .6 | 72.2 – 72.8 |
| Conglomerate, as in 45.0–46.0 ft | .1 | 72.8 – 72.9 |
| Sandstone, as in 43.0–45.0 ft | .6 | 72.9 – 73.5 |
| Conglomerate, as in 45.0–46.0 ft | 1.3 | 73.5 – 74.8 |
| Sandstone, as in 43.0–45.0 ft | .5 | 74.8 – 75.3 |
| Conglomerate, as in 45.0–46.0 ft; contains reworked fragments of red and gray siltstone from Dewey Lake Redbeds | 1.0 | 75.3 – 76.3 |

[2] See the following table:

| | Melting point (°C) | Boiling point (°C) |
|---|---|---|
| Iron | 1,535 | 3,000 |
| Tin | 231.9 | 2,270 |
| Silver | 960 | 1,950 |
| Lead | 327 | 1,620 |
| Bismuth | 271 | 1,560±5 |
| Salt | 801 | 1,413 |
| Zinc | 419 | 907 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Gatuna Formation (Pleistocene (?))—Continued | | |
| Sandstone, as in 43.0–45.0 ft; contains reworked fragments of red and gray siltstone from Dewey Lake Redbeds | .4 | 76.3 – 76.7 |
| Conglomerate, as in 45.0–46.0 ft; contains reworked fragments of red and gray siltstone from Dewey Lake Redbeds | 1.7 | 76.7 – 78.4 |
| Clay, pale-reddish-brown (10*R* 5/4), very hard, dense; contains interwoven black carbonaceous material | .1 | 78.4 – 78.5 |
| Sandstone, as in 43.0–45.0 ft | 1.0 | 78.5 – 79.5 |
| Clay, as in 78.4–78.5 ft | .1 | 79.5 – 79.6 |
| Sandstone, as in 43.0–45.0 ft | 1.0 | 79.6 – 80.6 |
| Clay, as in 78.4–78.5 ft | .05 | 80.6 – 80.65 |
| Sandstone, as in 43.0–45.0 ft | .75 | 80.65– 81.4 |
| Sandstone, as in 43.0–45.0 ft; contains many thin lenses of clay (about 0.01 ft. thick) as described in 78.4–78.5 ft | 4.1 | 81.4 – 85.5 |
| Sand, pale-reddish-brown (10*R* 5/4), very fine grained to coarse-grained, subrounded to well-rounded, unconsolidated; contains a few large yellow-green quartz pebbles and clear and stained quartz grains, a few quartz crystals with subrounded faces, some small grains of calcareous cementing material, and reworked fragments of Dewey Lake Redbeds | 6.4 | 85.5 – 91.9 |
| Total thickness of Gatuna Formation | 48.9 | |
| Unconformity. | | |
| Dewey Lake Redbeds (Upper Permian): | | |
| Siltstone, sandy, pale-reddish-brown (10*R* 5/4), well-indurated; contains light-greenish-gray (5*GY* 8/1), reduction spots and fine silt; calcite crystals and clusters dispersed throughout rock; has calcareous cement | 1.7 | 91.9 – 93.6 |
| Siltstone, as above except contains some clayey layers | 3.7 | 93.6 – 97.3 |
| Clay, pale-reddish-brown (10*R* 5/4), very dense; contains interspresed black carbon spots, and silty streaks containing reduction spots | .1 | 97.3 – 97.4 |
| Siltstone, as in 91.9–93.6 ft | 4.6 | 97.4 – 102.0 |
| Siltstone, light-greenish-gray (5*GY* 8/1), fine-grained, well-indurated; contains calcite crystals in clusters and interspersed throughout rock; has calcareous cement | .4 | 102.0 – 102.4 |
| Siltstone, as in 91.9–93.6 ft | 3.6 | 102.4 – 106.0 |
| Siltstone, as above but darker and finer grained; contains lenses of white very fine grained sandstone | .7 | 106.0 – 106.7 |
| Siltstone, as in 91.9–93.6 ft | 4.3 | 106.7 – 111.0 |
| Siltstone, as in 91.9–93.6 ft. but contains thin wavy bands of gray siltstone which extend around shaft | 1.1 | 111.0 – 112.1 |
| Dewey Lake Redbeds (Upper Permian)—Continued | | |
| Siltstone, pale-reddish-brown (10*R* 5/4), well-indurated, mostly thin-bedded; contains light-greenish-gray (5*GY* 8/1) reduction spots; calcite crystals in clusters dispersed throughout rock and fill joints; contains thin bands of clay or clayey material and black spots of manganese or oil(?) in joints and porous strata; has calcareous cement | 10.5 | 112.1 – 122.6 |
| Siltstone, same as above but contains thin lenses of sandstone | 8.1 | 122.6 – 130.7 |
| Siltstone, as in 102.0–102.4 ft | .4 | 130.7 – 131.1 |
| Siltstone, as in 122.6–130.7 ft; contains 0.5-ft-thick layers of siltstone as in 102.0–102.4 ft | 13.9 | 131.1 – 145.0 |
| Siltstone, same as above; contains 1-mm-thick bands of selenite crystals | 8.0 | 145.0 – 153.0 |
| Siltstone, sandy, pale-reddish-brown (10*R* 5/4), well-indurated to very friable; contains light-greenish-gray (5*GY* 8/1) reduction spots and thin layers; sand grains well rounded; has calcareous cement | 16.0 | 153.0 – 169.0 |
| Siltstone, as in 112.1–122.6 ft; jointing in interval 169–133 ft, as follows: Strike N. 70° W., dip 75° N.; strike N. 20° W., dip approximately 85° E.; bedding strikes N. 45° E., dips 4° NW; reduction spots in vertical zone tapering from 8 to 0 in.; apparently following fractures; from 175 to 178 ft, some reduction spots 1 ft in diameter; joints at 200 ft strike N. 30° W., dip 70° NE.; joints at 216 ft strike N. 90° E., dip 75° N.; calcite fills veins; joints at 278–284 ft strike N. 30° W., dip 50° N. to vertical | 125.0 | 169.0 – 294.0 |
| Total thickness of Dewey Lake Redbeds | 202.1 | |
| Unconformity. | | |
| Rustler Formation (Upper Permian): | | |
| Forty-niner Member: | | |
| Gypsum rock, white (*N* 9) to olive-gray (5*Y* 5/1); crystals 1–5 mm long; upper contact, with the Dewey Lake Redbeds at 294 ft, undulating and marked by green clay seam about 0.5 in. thick underlain by gray clay layer about 0.06 in. thick between red beds and white gypsum; gypsum grades into anhydrite from 298 to 300 ft with no definite contact, either laterally or vertically | 6.0 | 294.0 – 300.0 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Rustler Formation (Upper Permian)—Continued | | |
| Forty-niner Member—Continued | | |
| Anhydrite rock, olive-gray (5*Y* 5/1), massive, crystalline; contains some gypsum crystals; grades into gypsum above and below; white and pink fibrous gypsum and many fractures present at 315 ft; slickensides present at 316 ft | 22.0 | 300.0 – 322.0 |
| Gypsum rock, white (*N* 9) to olive-gray (5*Y* 5/1), massive, crystalline; contains white and pink fibrous gypsum at 325 ft and white and gray bands throughout | 6.5 | 322.0 – 328.4 |
| Siltstone, greenish-gray (5*GY* 7/1); well-indurated; has calcareous cement | .2 | 328.4 – 328.6 |
| Siltstone, sandy, pale-reddish-brown (10*R* 5/4), well-indurated to friable; contains some brecciated layers, fragments of gypsum, and light-greenish-gray reduction spots; has mostly calcareous cement; some clay lenses | 11.0 | 328.6 – 339.6 |
| Gypsum, breccia, grayish-red (10*R* 4/2) well-indurated; contains 1- to 2-cm long fragments of clear, red, and gray gypsum and fragments of gray and red siltstone; has calcareous cement | 1.0 | 339.6 – 340.6 |
| Gypsum rock, banded, pinkish-gray (5*YR* 8/1) and pale-red (10*R* 6/2), massive, crystalline; gradational with breccia above; red bands appear to be stylolitic; some patches of anhydrite grade into gypsum in lower 10 ft; lower 6 ft has 1-cm-thick fibrous veins of white gypsum approximately parallel to the bedding and about 5 cm apart; gypsum breccia at 359 ft | 20.7 | 340.6 – 361.3 |
| Total thickness of Forty-niner Member | 67.3 | |
| Magenta Member: | | |
| Dolomite rock, red-purple (magenta) (5*RP* 5/2), massive; contains white 1-mm-thick bands of selenite about 1 cm apart and scattered crystals of selenite in dolomite; cement dolomitic or calcareous; has fractures 1–5 cm wide filled with selenite | 6.8 | 361.3 – 368.1 |
| Siltstone, light-brownish-gray (5*YR* 6/1) to moderate-red (5*Y* 5/4); layers of siltstone alternate with irregular bands of selenite; has dolomitic or calcareous cement; beds range from paper thin to 0.5 ft thick | 3.6 | 368.1 – 371.7 |
| Rustler Formation (Upper Permian)—Continued | | |
| Magenta Member—Continued | | |
| Dolomite rock, silty, gypsiferous, pale-red (5*R* 6/2) to light-gray (*N* 7), thin-bedded; contains 1-mm to 1-cm-thick wavy bands of fibrous gypsum parallel to bedding; has wavy botryoidal bedding in lower 6 ft; joints strike N. 90° E., dip 84° N., and strike N. 10° E., dip 84° W.; bedding strikes north, dips 7° E; cluster of black manganese(?) in red and colorless fibrous gypsum at 379 ft | 10.5 | 371.7 – 382.2 |
| Total thickness of Magenta Member | 20.9 | |
| Tamarisk Member: | | |
| Anhydrite rock and gypsum rock, pale-red (10*R* 6/2) to light-olive-gray (5*Y* 6/1); contains 1-cm-thick bands of fibrous gypsum parallel to bedding; anhydrite grades into gypsum; some small irregular masses of gypsum throughout massive anhydrite rock microcrystalline; 1-cm.thick red clay layer at 403.5 ft in north wall of shaft; joint sets at 410–416 ft: strike N. 5° W., dip 75° W.; strike N. 25° E., dip 55° SE.; strike N. 90° E., dip 65° N.; strike N. 25° E., dip 55° NW.; joints cemented with selenite; joints at 432–438 ft strike N. 20° W. and dip 45° NE | 66.3 | 382.2 – 448.5 |
| Clay, brownish-black (5*YR* 2/1); plastic, slickensided; contains irregular fragments of fibrous gypsum; thickness ranges from 0.01 to 0.2 ft; dips 36° N. in shaft; this layer is at 440.5 ft in south wall | .1 | 448.5 – 448.6 |
| Anhydrite rock and gypsum rock, light-olive-gray (5*Y* 6/1); anhydrite and gypsum intergrade; massive anhydrite rock microcrystalline; contains large masses of fibrous and tabular gypsum; joint system strikes N. 55° E., dips 70° N.; folds in gypsum at 472–477 ft; a few thin gray plastic clay seams in gypsum at 477–480 ft | 31.4 | 448.6 – 480.0 |
| Clay, plastic, grayish-red (10*R* 4/2); interbedded gypsum fragments and crystals; selenite veins fill joints and occur along bedding; some cement grout in with selenite and clay; a few gray plastic clay seams at 484 ft; ground water seeps through wall, that has no visible openings | 5.0 | 480.0 – 485.0 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Rustler Formation (Upper Permian)—Continued | | |
| Tamarisk Member—Continued | | |
| Anhydrite rock and gypsum rock, light-olive-gray (5*Y* 6/1), banded; 2-in.-thick gray clay seam at 489 ft; contains thin bands of selenite | 10.5 | 485.0 – 495.5 |
| Total thickness of Tamarisk Member | 113.3 | |
| Culebra Dolomite Member: | | |
| Dolomite rock, dark-yellowish-brown (10*YR* 4/2), vesicular and vuggy, well-indurated; openings contain calcite crystals | .5 | 495.5 – 496.0 |
| Dolomite rock, yellowish-gray (5*Y* 8/1), microcrystalline, highly fractured, few vugs, poorly indurated | 3.3 | 496.0 – 499.3 |
| Dolomite rock, yellowish-gray (5*Y* 8/1), microcrystalline; contains brecciated zones, some of which fill vertical fractures; breccia recemented with pale-yellowish-brown (10*YR* 6/2) dolomite, mostly well indurated; contains zones of vesicular or "worm-eaten" dolomite, some of which are highly fractured; cement and chemical grout fill some openings; most vesicles spherical and range in diameter from a pinhead to about 1 inch; most openings not interconnected; some massive zones do not contain any openings | 24.2 | 499.3 – 523.5 |
| Total thickness of Culebra Dolomite Member | 28.0 | |
| Lower member: | | |
| Siltstone, medium-dark-gray (*N* 4), clayey, semiplastic; contains dolomite fragments from overlying unit | 1.7 | 523.5 – 525.2 |
| Clay, grayish-red (10*R* 4/2), very plastic; contains fragments and large breccia blocks from overlying units and grout; gypsum fragments mixed through the clay, and this mixture fills many openings in the dolomite; selenite band 0.5 in. thick at 527–530 ft | 9.3 | 525.2 – 534.5 |
| Gypsum rock and anhydrite rock, light-olive-gray (5*Y* 6/1), crystalline, massive; contains a few silty layers; some platy gypsum; beds strike N. 60° E., dip 16° NW.; joints strike N. 30° W., dip 86° S. at 541 ft; gray clay on south wall at 547 ft; beds strike N. 45° E., dip 10° NW. at 541–549 ft | 13.1 | 534.5 – 547.6 |
| Rustler Formation (Upper Permian)—Continued | | |
| Lower member—Continued | | |
| Claystone, grayish-red (10*R* 4/2) and light-gray (*N* 7), plastic; contains alternating layers of red and gray and gypsum bands and gypsum nodules; gray claystone very plastic and in irregular bands in red claystone; has some reduction zones; claystone absorbs water readily | 11.5 | 547.6 – 559.1 |
| Gypsum rock and anhydrite rock, as in 534.5–547.6 ft | 3.9 | 559.1 – 563.0 |
| Claystone, silty, moderate-reddish-brown (10*R* 4/6), poorly indurated; contact irregular, dips NW | 3.0 | 563.0 – 565.0 |
| Siltstone, clayey, sandy, grayish-red (10*R* 4/2); contains alternate discontinuous bands of light-olive-gray (5*Y* 6/1) gypsum; siltstone contains small selenite crystals and blebs of gypsum; no jointing obvious, bedding dips about 10° NW.; lens of gypsum and anhydrite 4 ft long and 1 ft thick at 564 ft in northwest wall | 6.0 | 565.0 – 571.0 |
| Gypsum rock, olive-gray (5*Y* 4/1), massive, crystalline, banded; beds dip about 10°–15° NW. in most of shaft but dip as much as 42° NW. in northwest wall | 1.0 | 571.0 – 572.0 |
| Siltstone, clayey, dark-reddish-brown (10*R* 3/4) and greenish-gray (5*GY* 5/1), laminated, noncalcareous; contains alternating layers of brown and gray; unconsolidated except for some partly consolidated lenses about 0.5 ft thick; more plastic from 577 to 579 ft; bedding dips northwest; sides of shaft spall off | 20.0 | 572.0 – 592.0 |
| Siltstone, clayey, sandy, olive-gray (5*Y* 5/1), very fine grained, poorly indurated, friable; contains blebs of gypsum crystals; shows crenulated wavy bedding, tends to spall off wall in some zones; a few zones fairly well indurated; rock predominantly angular to subrounded silt-size quartz but contains about 1 percent mafic minerals; rock disaggregates with effervescence in dilute HCl; bottom 2 ft of this unit fairly well indurated | 59.2 | 592.0 – 651.2 |
| Total thickness of lower member | 127.7 | |
| Total thickness of Rustler Formation | 357.2 | |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Salado Formation (Upper Permian): | | |
| Contact with Rustler Formation unconformable and very irregular. Top of Salado at 647.5 ft at southeast wall of shaft and at 660.0 ft at west wall of shaft. | | |
| Claystone breccia, grayish-red (10*R* 4/2 to 5/2); contains angular and subrounded fragments and blocks of gray siltstone, gypsum, and polyhalite ranging from sand size to 3 ft; contains discontinuous beds of gypsum and veins of fibrous gypsum; has zones of plastic red clay at 680–684 ft that taste salty | 36.0 | 651.2 – 687.2 |
| Claystone, medium-gray (*N* 5), plastic; contains abundant fragments and veins of colorless crystalline gypsum or selenite | .4 | 687.2 – 687.6 |
| Polyhalite rock, dark-reddish-brown (10*R* 3/4), crystalline, massive, platy; strikes N. 50° E., dip 18° NW | .9 | 687.6 – 688.5 |
| Siltstone, clayey, sandy, grayish-red (10*R* 4/2), calcareous; contains fragments of colorless crystalline gypsum | .3 | 688.5 – 688.8 |
| Claystone, plastic, poorly indurated; consists of very thin bands of dark-gray and grayish-red claystone containing veins and fragments of colorless crystalline gypsum | .4 | 688.8 – 689.2 |
| Siltstone, clayey, grayish-red (10*R* 5/2), calcareous; contains small amount of tiny fragments of clear gypsum and fragments of polyhalite | 4.3 | 689.2 – 693.5 |
| Gypsum rock, very pale orange (10*YR* 8/2) to light-brown (5*YR* 6/4), massive, microcrystalline; shows irregular stains of light-brown clay | .5 | 693.5 – 694.0 |
| Anhydrite rock, olive-gray (5*Y* 5/1), microcrystalline, massive | 12.0 | 694.0 – 706.0 |
| Claystone, medium-dark-gray (*N* 4), plastic; contains poorly indurated blocks of anhydrite | 2.0 | 706.0 – 708.0 |
| Anhydrite rock, olive-gray (5*Y* 4/1), massive microcrystalline; shows conchoidal fracture; bedding dips 5° NW | 1.2 | 708.0 – 709.2 |
| Claystone, light-gray (*N* 7), banded, well-indurated; probably alteration product of anhydrite above; interbedded with halite below | .1 | 709.2 – 709.3 |
| Halite rock, colorless to white; contains small blebs of moderate-reddish-orange (10*R* 6/7) halite and less than 1 percent gray clay | 1.7 | 709.3 – 711.0 |
| Halite rock, colorless to white; contains less than 1 percent small blebs of moderate-red (5*R* 4/6) clay | 4.5 | 711.0 – 715.5 |
| Claystone, pale-reddish-brown (10*R* 5/4) and light-gray (*N* 7); dips west at less than 1°; contains about 25 percent halite | .5 | 715.5 – 716.0 |
| Salado Formation (Upper Permian)—Continued | | |
| Halite rock; contains about 50 percent dark-reddish-brown (10*R* 3/4) clay | 3.5 | 716.0 – 719.5 |
| Halite rock; contains about 10 percent medium-light-gray (*N* 6) clay | 1.5 | 719.5 – 721.0 |
| Halite rock, colorless to white | 1.7 | 721.0 – 722.7 |
| Halite rock; contains about 5 percent medium-light-gray (*N* 6) clay; has irregular band of dark-reddish-brown (10*R* 3/4) clay at top which ranges from 0 to 1 ft thick | 2.5 | 722.7 – 725.2 |
| Claystone, plastic, dark-reddish-brown (10*R* 4/4) and medium-gray (*N* 5) | .4 | 725.2 – 725.6 |
| Halite rock, colorless; contains about 5 percent medium-gray (*N* 5) clay | 1.9 | 725.6 – 727.5 |
| Halite rock, colorless; contains blebs and spots of reddish-orange (10*R* 6/7) halite; contains less than 2 percent medium-gray (*N* 5) clay | 3.8 | 727.5 – 731.3 |
| Claystone, medium-dark-gray (*N* 4); irregular in thickness | .2 | 731.3 – 731.5 |
| Halite, colorless to white; contains some blebs of reddish-orange halite; thin discontinuous clay layer in lower 1 ft; clay content less than 1 percent | 9.7 | 731.5 – 741.2 |
| Polyhalite rock, orange | .7 | 741.2 – 741.9 |
| Halite rock, reddish-orange (10-*R* 6/7) to transparent white; at 742.6 ft contains 1.2-ft-thick reddish-brown clay layer | 6.0 | 741.9 – 747.9 |
| Halite rock, 5–10 percent reddish-brown clay; upper 2 ft contains 50 percent brown clay; unit contains several thin discontinuous clay seams and stringers and blebs of moderate-reddish-orange (10*R* 5/6) polyhalite | 13.1 | 747.9 – 761.0 |
| Halite rock; contains medium-gray clay band 0.1 ft thick at 762.0 ft, and dark-reddish-brown clay band 0.3 ft thick at 763.3 ft; above gray clay band is a double band of polyhalite separated by transparent colorless halite 0.2 ft thick (marker horizon(?)) | 5.0 | 761.0 – 766.0 |
| Halite rock, transparent colorless; contains three bands of thin moderate-orange-pink (10*R* 7/4) polyhalite | .9 | 766.0 – 766.9 |
| Halite rock, colorless transparent to white; contains blebs of moderate-orange-pink halite | 2.3 | 766.9 – 769.2 |
| Polyhalite rock, moderate-orange-pink (10*R* 7/4); contains 0.2-in.-thick band of halite in middle | .3 | 769.2 – 769.5 |
| Halite rock, white; contains less than 1 percent moderate-gray clay; some polyhalite blebs and stringers scattered throughout lower half | 4.1 | 769.5 – 773.6 |
| Claystone, dark-reddish-brown (10*R* 3/4), plastic; contains scattered crystals of halite; 0.5-in.-thick gray layer at top | 1.2 | 773.6 – 774.8 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Salado Formation (Upper Permian)—Continued | | |
| Halite rock; contains about 20 percent dark-reddish-brown clay; grades into overlying unit; irregular and discontinuous polyhalite band at 776.6 ft that averages 0.2 ft thick | 6.3 | 774.8 – 781.1 |
| Claystone, dark-reddish-brown (10*R* 3/4); dips less than 1° NW | .1 | 781.1 – 781.2 |
| Halite rock; contains about 35 percent dark-reddish-brown clay in blebs and discontinuous bands; contains about 2 percent polyhalite in blebs | 4.4 | 781.2 – 785.6 |
| Polyhalite rock about 0.1 ft thick overlying 0.1 ft of gray anhydrite rock | .2 | 785.6 – 785.8 |
| Halite rock; contains about 10–20 percent polyhalite in blebs and stringers and about 5 percent gray clay | 9.7 | 785.8 – 795.5 |
| Polyhalite rock; moderate-orange-pink (10*R* 7/4); contains 1-mm-thick discontinuous dark-gray clay band in middle | 1.4 | 795.5 – 796.9 |
| Claystone, medium-light-gray (*N* 6); contains about 20 percent halite | .3 | 796.9 – 797.2 |
| Halite rock, moderate-reddish-orange (10*R* 6/6); contains about 20 percent gray clay | .8 | 797.2 – 798.0 |
| Claystone, dark-reddish-brown; contains about 50 percent halite | 6.0 | 798.0 – 804.0 |
| Halite rock; upper 5 ft contains about 10–20 percent gray clay in blebs; lower 6 ft contains about 2 percent polyhalite in discontinuous stringers and blebs | 9.3 | 804.0 – 813.3 |
| Halite rock; contains about 20 percent polyhalite in blebs, stringers, and irregular masses | 5.2 | 813.3 – 818.5 |
| Claystone, medium-dark-gray (*N* 4) to medium-light-gray (*N* 6); contains about 25 percent halite | 2.1 | 818.5 – 820.6 |
| Claystone, same as next higher unit but contains about 10 percent polyhalite | 2.0 | 820.6 – 822.6 |
| Anhydrite rock, yellowish-gray (5*Y* 8/1), banded, vuggy; contains about 5 percent halite; some polyhalite blebs at top | 2.4 | 822.6 – 825.0 |
| Anhydrite rock, banded with gypsum and halite; gypsum and halite are dusky yellow (5*Y* 6/4); anhydrite is light gray (*N* 7); in other walls of shaft, more than 1 ft of polyhalite underlies this unit, but it pinches out and is absent from north wall | 2.5 | 825.0 – 827.5 |
| Claystone, medium-gray (*N* 5), plastic | .5 | 827.5 – 828.0 |
| Halite rock, transparent, colorless; contains about 5 percent gray clay in blebs and about 2 percent polyhalite | 3.3 | 828.0 – 831.3 |
| Anhydrite rock, light-gray (*N* 7) | .2 | 831.3 – 831.5 |
| Halite rock; contains about 20 percent polyhalite that occurs in discontinuous bands | 1.5 | 831.5 – 833.0 |
| Anhydrite rock, very light gray (*N* 8); banded upper foot contains some halite and polyhalite in discontinuous bands 0.8 ft thick | 2.5 | 833.0 – 835.5 |
| Halite rock, colorless to white; contains about 1 percent polyhalite in blebs and one band of anhydrite 1 in. thick | 1.3 | 835.5 – 836.8 |
| Anhydrite rock, very light gray (*N* 8), microcrystalline | .4 | 836.8 – 837.2 |
| Halite rock; contains a 1-mm-thick band of anhydrite and more than 1 percent gray clay in blebs | .8 | 837.2 – 838.0 |
| Anhydrite rock, very light gray (*N* 8), laminated; at 839.2–838.4 ft, contains breccia layer consisting of anhydrite fragments in clay matrix; at 839.8–840.1 ft, contains band of moderate-orange-pink (10*R* 7/4) to white halite; basal 0.3 ft contains gray clay and orange-pink halite | 6.3 | 838.0 – 844.3 |
| Halite, rock transparent, colorless;contains about 1 percent gray clay blebs | 6.9 | 844.3 – 851.2 |
| Claystone, medium-dark-gray (*N* 4); contains 2-mm-thick discontinuous bands of halite | .7 | 851.2 – 851.9 |
| Halite rock, transparent, colorless to moderate-orange-pink; contains about 20 percent medium-gray (*N* 5) and dark-reddish-brown (10*R* 3/4) clay in blebs and 5 percent moderate-orange-pink (10*R* 7/4) polyhalite | 1.1 | 851.9 – 853.0 |
| Halite rock, transparent, colorless to white; contains about 5 percent polyhalite in blebs | 1.9 | 853.0 – 854.9 |
| Halite rock; contains about 30–50 percent dark-reddish-brown (10*R* 3/4) clay | 1.5 | 854.9 – 856.4 |
| Halite rock, transparent, colorless to white; contains about 10 percent greenish-gray (5*GY* 6/1) clay in blebs and 1 percent polyhalite in blebs | 5.3 | 856.4 – 861.7 |
| Halite rock, transparent, colorless to white; contains about 2 percent medium-gray (*N* 5) clay and less than 1 percent polyhalite, both in blebs; separated from overlying unit by distinct change in amount of clay | 5.6 | 861.7 – 867.3 |
| Halite rock, white; contains about 5 percent medium-gray (*N* 5) clay and about 1 percent polyhalite in blebs; drill holes in sump at 874 ft have gas bubbling up | 9.4 | 867.3 – 876.7 |
| Polyhalite rock, moderate-reddish-orange (10*R* 6/6); contains about 25 percent halite | 1.8 | 876.7 – 878.5 |
| Claystone, light-gray (*N* 7); contains about 50 percent halite | 1.5 | 878.5 – 880.0 |
| Claystone, dark-reddish-brown (10*R* 3/4); contains about 25 percent halite | 1.5 | 880.0 – 881.5 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Salado Formation (Upper Permian)—Continued | | |
| Halite rock, colorless to orange; contains about 40 percent clay, both grayish red (10*R* 4/2) and greenish gray (5*GY* 6/1), and about 5 percent polyhalite in blebs | 5.0 | 881.5 – 886.5 |
| Polyhalite rock, moderate-reddish-orange (10*R* 6/6) | 1.0 | 886.5 – 887.5 |
| Halite rock, white to moderate-orange; upper foot contains about 5 percent light-gray (*N* 7) clay; remainder contains less than 1 percent clay; a discontinuous polyhalite bed at 895.5 ft averages 2 in. thick | 10.0 | 887.5 – 897.5 |
| Polyhalite rock, grayish-orange-pink (10*R* 8/2) | .3 | 897.5 – 897.8 |
| Halite rock, white; contains about 10 percent medium-gray (*N* 5) clay | .7 | 897.8 – 898.5 |
| Halite rock, moderate-reddish-orange (10*R* 6/6); contains 1 percent polyhalite in blebs near base | 2.3 | 898.5 – 900.8 |
| Halite rock, moderate-reddish-orange (10*R* 6/6); contains about 25 percent medium-gray (*N* 5) clay in bands; has 2-in.-thick band of dark-reddish-brown (10*R* 3/4) clay at base | 1.5 | 900.8 – 902.3 |
| Halite rock, transparent, colorless; contains about 30 percent dark-reddish-brown (10*R* 3/4) clay | 1.7 | 902.3 – 904.0 |
| Halite rock, white; contains about 10 percent greenish-gray (5*GY* 6/1) clay in blebs and bands; contains about 1 percent polyhalite in blebs | 8.1 | 904.0 – 912.1 |
| Halite rock, clear; contains about 25 percent medium-light-gray (*N* 6) clay | .6 | 912.1 – 912.7 |
| Halite rock, transparent, colorless to moderate-orange-pink (10*R* 7/4); contains discontinuous 1-in.-thick bands of polyhalite | 2.0 | 912.7 – 914.7 |
| Polyhalite rock, moderate-reddish-orange (10*R* 6/6); contains irregular discontinuous bands of transparent, colorless halite | .7 | 914.7 – 915.4 |
| Claystone, medium-light-gray (*N* 6); thickness ranges from featheredge to 0.2 ft | .2 | 915.4 – 915.6 |
| Halite rock; contains about 2 percent gray clay and about 1 percent polyhalite in blebs | 4.2 | 915.6 – 919.8 |
| Halite rock; contains about 20 percent of both gray and reddish-brown clay and about 10 percent polyhalite; 0.2-ft-thick bed of polyhalite present at 920 ft | 1.2 | 919.8 – 921.0 |
| Halite rock; contains about 5 percent gray clay in blebs and about 2 percent polyhalite in blebs | 6.6 | 921.0 – 927.6 |
| Halite rock; contains about 10 percent polyhalite in blebs and bands; bottom 1 foot contains about 50 percent polyhalite in alternating bands with halite | 3.9 | 927.6 – 931.5 |
| Claystone, dark-reddish-brown (10*R* 3/4); contains about 40 percent halite | 1.5 | 931.5 – 933.0 |
| Halite rock; contains about 10 percent medium-gray (*N* 5) clay and about 5 percent polyhalite in blebs and discontinuous layers | 10.2 | 933.0 – 943.2 |
| Polyhalite rock in layers 0.1–0.3 ft thick alternating with halite | 1.8 | 943.2 – 945.0 |
| Halite rock, white; contains less than 1 percent polyhalite in blebs | 2.5 | 945.0 – 947.5 |
| Halite rock, moderate-reddish-orange (10*R* 6/6); appears to be layered in about 0.5-ft-thick layers owing to variations in color; contains thin (1 mm) bands of white opaque halite; becomes darker orange near base | 8.0 | 947.5 – 955.5 |
| Polyhalite rock; lower half contains thin (2 mm) bands of clay | 1.0 | 955.5 – 956.5 |
| Halite rock; contains about 1 percent polyhalite in blebs; contains about 5 percent gray clay from 960 to 960.7 ft | 2.5 | 956.5 – 959.0 |
| Claystone, medium-dark-gray (*N* 4); contains about 50 percent halite | 1.0 | 959.0 – 960.0 |
| Claystone, dark-reddish-brown (10*R* 3/4); contains about 50 percent halite | 3.0 | 960.0 – 963.0 |
| Halite rock; contains about 20 percent dark-reddish-brown (10*R* 3/4) clay and about 5 percent polyhalite in blebs | 1.0 | 963.0 – 964.0 |
| Halite rock; contains about 25 percent polyhalite | 1.5 | 964.0 – 965.5 |
| Anhydrite rock, yellowish-gray (5*Y* 8/1), dense, fine-grained; contains crystalline grayish-orange (10*YR* 7/4) anhydrite | 1.5 | 965.0 – 967.0 |
| Halite rock, transparent, colorless to white; contains 0.1- to 0.2-ft-thick bands of polyhalite separated by 0.2- to 1-ft-thick layers of halite | 5.7 | 967.0 – 972.7 |
| Polyhalite rock, moderate-reddish-orange (10*R* 6/6) | .4 | 972.7 – 973.1 |
| Anhydrite rock, yellowish-gray (5*Y* 8/1), banded in 0.5-in.-thick layers | .9 | 973.1 – 974.0 |
| Halite rock, colorless to white; contains about 10–20 percent polyhalite in blebs and thin layers, and about 2 percent gray clay in blebs; 0.2-ft-thick discontinuous layer of polyhalite present at 981.5 ft | 11.2 | 974.0 – 985.2 |
| Halite rock; contains about 10 percent medium-dark-gray (*N* 4) clay and 1 percent polyhalite; has 0.2-ft-thick bed of medium-dark-gray clay at base | 1.4 | 985.2 – 986.6 |
| Halite rock; contains about 50 percent dark-reddish-brown (10*R* 4/6) clay | 3.4 | 986.6 – 990.0 |
| Halite rock; contains thin bands of polyhalite | 2.8 | 990.0 – 992.8 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Salado Formation (Upper Permian)—Continued | | |
| Polyhalite rock, moderate-red (5*R* 5/4) | 0.1 | 992.8 - 992.9 |
| Halite rock, transparent, colorless; contains about 10–15 percent greenish-gray (5*G* 6/1) clay in irregular layers and about 2 percent polyhalite in blebs; halite coarsely crystalline, occurring as 1-in. crystals | 7.6 | 992.9 -1,000.5 |
| Halite rock, white to colorless, transparent; contains less than 1 percent polyhalite in thin irregular streaks | 2.5 | 1,000.5 -1,003.0 |
| Polyhalite rock, grayish-orange-pink ( *YR* 7/2), banded; from 1,003 to 1,004 ft consists mainly of polyhalite and halite with some anhydrite bands; anhydrite is microcrystalline and spalls and shatters when struck. One joint set strikes N. 50° E., dips 65° NW.; another set is normal to this; joints spaced about 0.5 ft apart | 4.0 | 1,003.0 -1,007.0 |
| Anhydrite rock, light-olive-gray (5*Y* 6/1), banded in ¼-in.-thick bands; basal 0.5 ft contains medium-gray clay (*N* 5) and gypsum | 2.2 | 1,007.0 -1,009.2 |
| Halite rock, transparent, colorless to moderate-reddish-orange; contains about 2 percent polyhalite in blebs | 3.1 | 1,009.2 -1,012.3 |
| Polyhalite rock, pale-reddish-brown (10*R* 5/4); contains several thin gray clay seams | 1.7 | 1,012.3 -1,014.0 |
| Halite rock, medium-light-gray (*N* 6); contains about 10 percent clay | .9 | 1,014.0 -1,014.9 |
| Halite rock; in alternating white and pale-yellowish-orange (10*YR* 8/6) bands 0.2–0.3 ft thick | 5.9 | 1,014.9 -1,020.8 |
| Halite rock; alternates with irregular bands of silty dark-reddish-brown (10*R* 3/4) clay; contains about 50 percent clay; contains 2 percent polyhalite in blebs near top of unit | 3.5 | 1,020.8 -1,024.3 |
| Siltstone, clayey, pale-reddish-brown (10*R* 5/4); contains light-gray (*N* 7) clay blebs. (With subjacent unit is Vaca Triste Sandstone Member of Adams (1944).) | 2.0 | 1,024.3 -1,026.3 |
| Siltstone, clayey, pale-reddish-brown (10*R* 5/4); contains about 50 percent halite | 2.7 | 1,026.3 -1,029.0 |
| Halite rock; top 3 ft contains about 40 percent dark-reddish-brown (10*R* 3/4) clay; basal 2 ft contains about 5 percent polyhalite in blebs and stringers | 5.7 | 1,029.0 -1,034.7 |
| Halite rock; contains about 20 percent light-gray (*N* 7) clay | 1.4 | 1,034.7 -1,036.1 |
| Halite rock, transparent, colorless; contains about 10 percent polyhalite in irregular layers and blebs | 3.5 | 1,036.1 -1,039.6 |
| Salado Formation (Upper Permian)—Continued | | |
| Halite rock; contains about 10 percent light-gray (*N* 7) clay in irregular thin bands and blebs | 0.9 | 1,039.6 -1,040.5 |
| Halite rock, transparent, colorless; contains about 5 percent polyhalite in irregular horizontal stringers and blebs; contains 1-cm-thick band of light-gray (*N* 7) clay at 1,043.3 ft | 4.0 | 1,040.5 -1,044.5 |
| Claystone, light-gray (*N* 7); contains about 50 percent halite; has 0.1-ft-thick layer of dark-reddish-brown (10*R* 3/4) clay at base | 2.1 | 1,044.5 -1,046.6 |
| Halite rock, white to colorless, transparent; contains about 10 percent polyhalite in blebs; irregular clayey zone present at 1,057 ft; interval 1,053–1,057 ft contains about 2 percent polyhalite in discontinuous layers; irregular band of gray clay at base averages 0.05 ft thick | 10.4 | 1,046.6 -1,057.0 |
| Claystone, dark-reddish-brown (10*R* 3/4); contains about 30–40 percent halite; discontinuous gray clay layers at top | 2.0 | 1,057.0 -1,059.0 |
| Halite rock, white to colorless; contains about 1 percent polyhalite in blebs and thin bands and about 10–20 percent of both red and gray clay in irregular bands and disseminated blebs; layer at 1,061–1,063 ft contains about 40 percent clay; unit contains gas under pressure | 5.3 | 1,059.0 -1.064.3 |
| Polyhalite rock; underlain by 0.5 in. light-gray (*N* 7) clay | .2 | 1,064.3 -1,064.5 |
| Halite rock; contains about 5 percent polyhalite in stringers and blebs | 2.8 | 1,064.5 -1.067.3 |
| Claystone, pale-red (10*R* 6/2); top 0.2 ft light-gray (*N* 7) clay; unit contains about 5 percent halite; gas present in this unit | 3.7 | 1,067.3 -1,071.0 |
| Halite rock, white to colorless; contains less than 1 percent polyhalite in blebs and less than 1 percent red clay in blebs | 3.5 | 1,071.0 -1,074.5 |
| Halite rock, transparent, colorless; contains about 5 percent polyhalite in irregular discontinuous bands; contains a few 2-mm-thick layers of brown clay at 1,078–1,083.4 ft | 9.0 | 1,074.5 -1,083.5 |
| Halite rock; contains about 25 percent medium-light-gray (*N* 6) clay | .9 | 1,083.5 -1,084.4 |
| Halite rock; contains about 40 percent pale-reddish-brown (10*R* 5/4) clay; basal contact irregular | 4.6 | 1,084.4 -1,089.0 |
| Halite rock; contains about 10 percent polyhalite in irregular horizontal bands about 1 in. thick; upper part of unit contains vertical stringers of medium-gray (*N* 5) clay | 7.0 | 1,089.0 -1,096.0 |

| Description | Thickness (ft) | Depth (ft) |
|---|---|---|
| Salado Formation (Upper Permian—Continued | | |
| Polyhalite rock; upper half contains about 10 percent halite in blebs | 1.0 | 1,096.0 –1,097.0 |
| Polyhalite rock, banded; 0.2-ft-thick medium-gray (*N* 5) clay layer at base | 1.6 | 1,097.0 –1,098.6 |
| Halite rock, colorless to white; contains less than 1 percent polyhalite in blebs and less than 1 percent gray clay in blebs | 11.7 | 1,098.6 –1,110.3 |
| Halite rock; contains about 30–50 percent pale-reddish-brown (10*R* 5/4) clay, and contains about 1 percent polyhalite in blebs near top; clay in top and bottom 1 foot is gray | 5.2 | 1,110.3 –1,115.5 |
| Halite rock, colorless to white; contains 10–20 percent stringers and blebs of polyhalite; 0.1-ft-thick layer of polyhalite underlain by 0.05-ft-thick layer of gray clay at base | 1.9 | 1,115.5 –1,117.4 |
| Halite rock; contains about 25 percent medium-light-gray (*N* 6) clay in upper part; basal 2 ft contains no clay | 2.9 | 1,117.4 –1,120.3 |
| Anhydrite rock; in alternating grayish-orange (10*YR* 7/4) and very light gray (*N* 8) bands; contains scattered blebs and lenses of polyhalite and halite; 0.2-ft-thick gray clay layer at base | 3.9 | 1,120.3 –1,124.2 |
| Halite rock, colorless to moderate-reddish-orange (10*R* 6/6); contains a band of grayish-orange-pink (5*YR* 7/2) anhydrite from 1,125.5 to 1,125.8 ft; contains gas | 3.1 | 1,124.2 –1,127.3 |
| Polyhalite rock, banded, grayish-orange-pink (5*YR* 7/2); 0.05 ft of gray clay at base | .5 | 1,127.3 –1,127.8 |
| Halite rock, in alternating white and moderate-reddish-orange (10*R* 6/6) bands; contains discontinuous clayey zones near top and base | 3.0 | 1,127.8 –1,130.8 |
| Claystone, grayish-red (10*R* 4/2); contains about 30 percent halite; 0.05-ft-thick layer of gray clay at top; contains irregular bands of polyhalite and halite in interval 1,131.2–1,131.8 ft | 4.0 | 1,130.8 –1,134.8 |
| Halite rock; contains about 50 percent polyhalite and about 10 percent gray clay | 1.0 | 1,134.8 –1,135.8 |
| Claystone, greenish-gray (5*GY* 6/1); contains about 50 percent halite, and inclusions of grayish-red (10*R* 4/2) clay; lower contact gradational | 2.0 | 1,135.8 –1,137.8 |
| Halite rock, transparent colorless; contains vaguely defined bands of moderate-reddish-orange (10*R* 6/5) halite and 2- to 4-mm-thick bands of anhydrite in the lower half | 18.2 | 1,137.8 –1,156.0 |
| Salado Formation (Upper Permian—Continued | | |
| Polyhalite rock, moderate-reddish-brown (10*R* 4/6); contains several plastic medium-gray (*N* 5) clay layers 2–5 mm thick; contains lenses of halite. (Marker bed 119) | 1.0 | 1,156.0 –1,157.0 |
| Claystone, medium-gray (*N* 5); irregular in thickness | .7 | 1,157.0 –1,157.7 |
| Halite rock, moderate-reddish-orange (10*R* 6/5); contains about 10 percent polyhalite in blebs, and about 5 percent gray clay in layers | 2.3 | 1,157.7 –1,160.0 |
| Claystone, medium-gray (*N* 5); contains about 30–50 percent halite and about 2 percent polyhalite near base | 8.0 | 1,160.0 –1,168.0 |
| Halite rock, transparent, colorless; contains about 2 percent gray clay in blebs and 2 percent polyhalite in blebs; at 1,170 ft is moderate reddish orange (10*R* 6/6) | 8.5 | 1,168.0 –1,176.5 |
| Polyhalite rock; contains discontinuous lenses of halite; grades into overlying unit. (Marker bed 120) | 1.5 | 1,176.5 –1,178.0 |
| Halite rock, moderate-reddish-orange (10*R* 6/6) | .7 | 1,178.0 –1,178.7 |
| Halite rock; contains about 25 percent gray clay; top 0.2 ft is medium-gray (*N* 5) clay layer | .7 | 1,178.7 –1,179.4 |
| Halite rock, banded white and moderate-reddish-orange (10*R* 6/6); contains about 5 percent polyhalite in blebs and lenses | 4.6 | 1,179.4 –1,184.0 |
| Halite rock; contains about 2 percent polyhalite in blebs and 2 percent gray clay in blebs | 1.0 | 1,184.0 –1,185.0 |
| Halite rock, colorless; contains about 25–30 percent clay both reddish brown and gray in blebs; grades downward into underlying unit | 6.0 | 1,185.0 –1,191.0 |
| Halite rock; contains about 10 percent polyhalite in blebs | 2.7 | 1,191.0 –1,193.7 |
| Polyhalite rock; 0.1-ft-thick bed of gray clay at base. (Marker bed 121) | .9 | 1,193.7 –1,194.6 |
| Halite rock; contains about 2 percent gray clay and 2 percent polyhalite in blebs | 7.4 | 1,194.6 –1,202.0 |
| Total partial thickness of Salado Formation | 550.8 | |

Bottom of shaft.

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