UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# SUMMARY OF GEOLOGIC INVESTIGATIONS, CYCLONE PROJECT

## Part II. Geology of the USGS Tunnel and Underground Effects of the High Explosives Tests

*By J. M. Cattermole*

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### Introduction

The USGS tunnel was driven as part of an experiment conducted by the U. S. Geological Survey for the Atomic Energy Commission to determine the effects of detonating large charges of high explosives underground. Two major tests were conducted. In the first of these, a charge of 10 tons of dynamite was detonated beneath 123.4 feet of vertical cover. In the second, a charge of 50 tons of dynamite was detonated beneath 174.1 feet of vertical cover. In addition to these tests, a series of small dynamite charges was exploded in shallow drill holes to determine the cover necessary for containment at various depths.

The USGS tunnel is located in the northwest part of the Nevada Test Site in the Tippipah Spring quadrangle. The portal of the tunnel is at an elevation of 5,585 feet above sea level. The tunnel is driven into a ridge, about 300 feet high, that is a low spur of the Belted Range. Just south of the tunnel site an alluvium-filled valley drains into Yucca Flat about a mile to the east. The surface geology of the area is described in Part I of this report.

The underground workings consist of the main tunnel, 308 feet long, oriented N. 22$^{\circ}$ E., and two laterals leading to Room A and Room B at right angles to the main tunnel (see fig. 8). The lateral to Room B was designed with a turn back upon itself with the

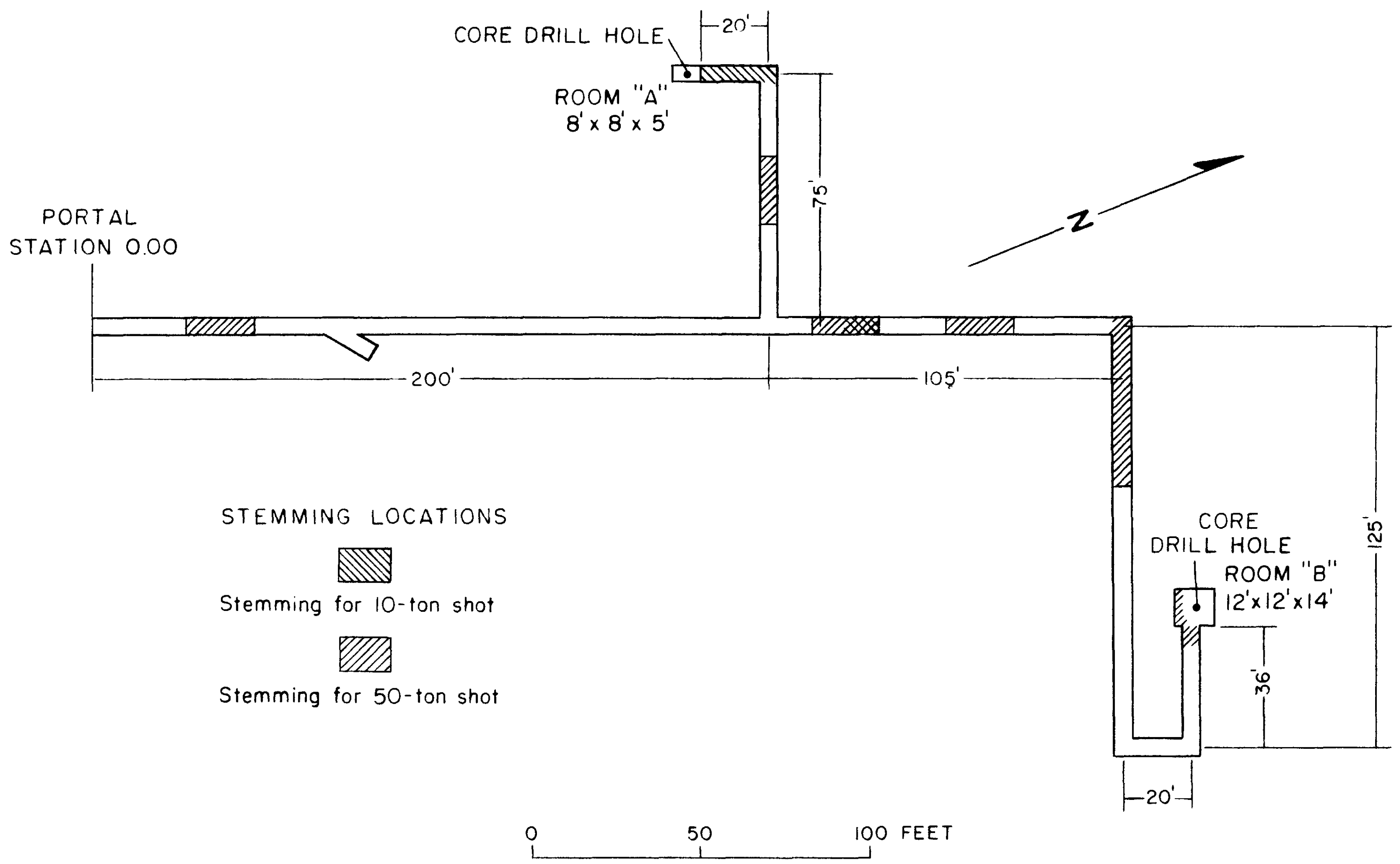



FIGURE 8. PLAN OF U.S.G.S. TUNNEL SHOWING STEMMING

expectation that at the instant of the explosion blocks of rock would be driven across and into the lateral, sealing it and confining the explosive forces to Room B and its immediate vicinity. Specifications called for the main tunnel and laterals to be 4 feet wide by 6.5 feet high; Room A was to be 5 feet wide, 8 feet long and 8 feet high; Room B was to be 11 feet in all dimensions. In the actual excavation the tunnel dimensions were somewhat irregular, Room A was essentially as specified, and Room B was approximately 12 feet wide, 12 feet high, by 14 feet in its northerly direction.

Prior to the explosion the geology of the underground workings was mapped at a scale of one inch equals 10 feet. After each explosion the workings were remapped to establish the effects, the limits and kind of damage sustained by the workings and the rocks. To illustrate the effects underground a projection was chosen in which the details of both walls and the back (ceiling) are represented (fig. 7, parts A, B, and C; scale one inch equals 20 feet). In this projection the center strip is the plan of the back; the two strips adjacent to the plan are the profiles of the walls rotated outward to the horizontal plane along the line of junction between the top of the walls and the back. In the mapping before the explosions the tunnel was assumed to be rectangular, and where departure from the assumed rectangular shape did occur the attitude of the feature mapped was projected to intersect the plane of the assumed rectangle. The stratigraphic units, bedding attitudes, faults, and all fractures were mapped.

The term fracture, as used here, includes joints, seams, and faults of only slight displacement. Figure 7, Geology of the USGS tunnel and underground effects of the high explosives tests, part A, is the original (pre-shot) geology; figure 7, part B, effect of 10-ton shot on geology and workings; figure 7, part C, effect of 50-ton shot on geology and workings.

## Geology

The tunnel was driven in the bedded volcanic tuffs of the Oak Spring formation described in the section "Stratigraphy of the USGS tunnel site" in part I of this report. These tuffs have a low specific gravity (1.35 to 1.7), are easy to drill and blast, and stand very well without timbering.

The portal of the tunnel started in Bed 20 (see table 1, part I). Underground the strike of the bedding is variable but has a persistent northerly component; dips are 7° to 15° eastward. The main tunnel, oriented N. 22° E., cuts progressively higher beds in the stratigraphic section from the portal to sta. 2+65_/ where one of the largest faults of the USGS site crosses the tunnel as shown on figure 1. The surface trace of this fault runs from a point about 110 feet southeast of the portal through a point on the ridge directly over Room B. The fault is normal, strikes north and dips 65° W. The east side is upthrown bringing Bed 19c up against

_/ All stationing is measured from a zero point at the tunnel portal; thus sta. 2+65 is 265 feet from the portal in the main tunnel, sta. 2+16 W. is 16 feet from sta. 2+00, main tunnel, measured to a point in the west lateral to Room A.

Bed 22d on the west of the fault at tunnel level. The hanging wall for about 20 feet west of the fault is broken and disturbed by criss-cross fractures; the footwall is relatively unfractured, but is marked by one to 3 inches of red-brown gouge. Beyond the fault, in the upthrown block, the main tunnel and the east lateral again cut upward through the section from Bed 19c, sta. 2+65, to the base of Bed 20 (portal bed) which is exposed in the back at sta. 4+50.

From sta. 2+00 the west lateral to Room A cuts down in the section to the top of Bed 20 (portal bed) which is at grade line at the entrance to Room A. At sta. 2+00 and in the first 8 to 10 feet of the west lateral, there was evidence of pre-explosion interbed slippage between the top of Bed 21 and the base of Bed 22a. The upper 0.5 foot of Bed 21, underground, is a soft plastic clay grit which is overlain by about 2.5 feet of porcellanite tuff of Bed 22a. This bedding plane, which proved to be an important horizon after both explosions, resembled a ripple-marked surface with about one foot between crests of the ripples.

The only fault of any consequence encountered in the underground workings was the one already described at sta. 2+65. Three minor faults with displacements of a foot or less were cut by the east lateral to Room B. In addition, a shear zone in the northeast corner of Room B consisted of four main vertical fractures striking north to northeast. A manganese stained bedding plane was not displaced from one side of this shear zone to the other, but was displaced upward 6 inches to one foot within the shear zone.

The net displacement of the entire zone, therefore, was nil. In the main tunnel between sts. 1/11 and sta. 1/19 as well as in the west lateral to Room A between sta. 2/37 W. and sta. 2/44 W. the rock was sheared, but displacements were negligible.

Jointing was conspicuous in some parts of the underground workings but not in others. The controlling factor of jointing apparently was the lithology and not the degree of deformation to which the strata had been subjected. The stronger, more brittle, beds were jointed upon deformation; the weaker beds especially those altered to a zeolitic matrix, absorbed the stresses of deformation without fracturing. The strike of joints vary in direction, but a plot of their strikes shows a preferred northerly orientation. Consequently the majority of the joints parallel, or are at a slight angle to the main tunnel, and are perpendicular to the laterals. Most of the joints are steep or vertical. Generally the fractures seen underground were bordered by weathered zones one-fourth inch wide indicative of alteration by ground water percolating along the openings.

## Underground Effects of the High Explosive Tests

### 10-ton Explosion

The first part of the high explosive test was the detonation of 10 tons of dynamite in Room A. All the underground workings--main tunnel, laterals, and Room A and Room B--had been excavated and completely mapped prior to this test. The rock cover vertically over the charge was 123.4 feet but because of the configuration of the hill the minimum distance to the surface was 92 feet measured southwesterly from the center of Room A.

The dynamite used was 60 percent nitroglycerin gelatin packed in 50 pound cylinders. The specified dimensions of Room A, 5x8x8 feet, had been calculated as the size necessary to hold the dynamite charge. Irregularities of the floor and walls prevented complete orderly stacking, however, and the charge as finally loaded extended 1.5 feet into the entrance lateral.

As it would be necessary to work in the tunnel for a few days after the dynamite was placed and armed, Primacord was selected as the safest means of detonation. The Primacord was laced through each layer of the dynamite and strands were run to the portal where it was to be set off by electric caps in a remote control circuit.

The entrance lateral to Room A, from the dynamite charge to the north wall of sta. 2+75 W., was stemmed tight with sandbags (fig. 8). A sandbag barrier was also placed in the main tunnel between sta. 2+30 and sta. 2+35 to protect the workings to Room B. The bags were filled with finely crushed limestone aggregate from Frenchman Flat.

The charge was set off on February 21, 1957 at 2:01:01 p.m. At the instant of the explosion the surface above Room A was seen to rise a few feet and then settle back. A second or two later a dust cloud issued from the portal of the tunnel and shot in a directed, jet-like stream into the valley south of the site for hundreds of feet. Immediately after the explosion a large area on the surface over Room A was seen to have been fissured and deformed by the blast (see part I of this report). The odor of dynamite fumes was strong, particularly near the fissures that had been opened. Bureau of Standards colorimetric test equipment indicated a high concentration of fumes in the tunnel. A blower and barricade were set up and the tunnel was ventilated for two days before starting clean-up work.

After the explosion the main tunnel between the portal and the sandbag barrier at sta. 2+30 was choked with more than 200 cubic yards of debris (fig. 9). This muck increased in depth from about 6 inches at the portal to an average of 5 feet at sta. 2+00 and beyond to the sandbag barrier at sta. 2+30. At first there appeared to be a sorting of the muck, fines in some sections of the tunnel alternating with coarse material in other sections. In post-shot remapping it was found that the coarse material, particularly that of boulder size, had spalled from the walls or back fairly close to the place of repose. The west lateral was swept clean of all fine material; the large boulders in this lateral had been transported into it from the explosion cavity.

When the debris was cleared from the main tunnel, it became apparent that a new opening that bypassed the stemming had been blown through previously undisturbed rock from the site of Room A diagonally across to intersect the west lateral between sta. 2+48 W. and sta. 2+59 W. (fig. 10). The lateral from sta. 2+59 W. to sta. 2+69 W. was closed completely by a block of rock. This block was fractured but retained bedding planes in apparently normal attitude. The fault bounding the block at the top was a knife sharp plane with direction of movement, N. $62^{\circ}$ E., clearly illustrated

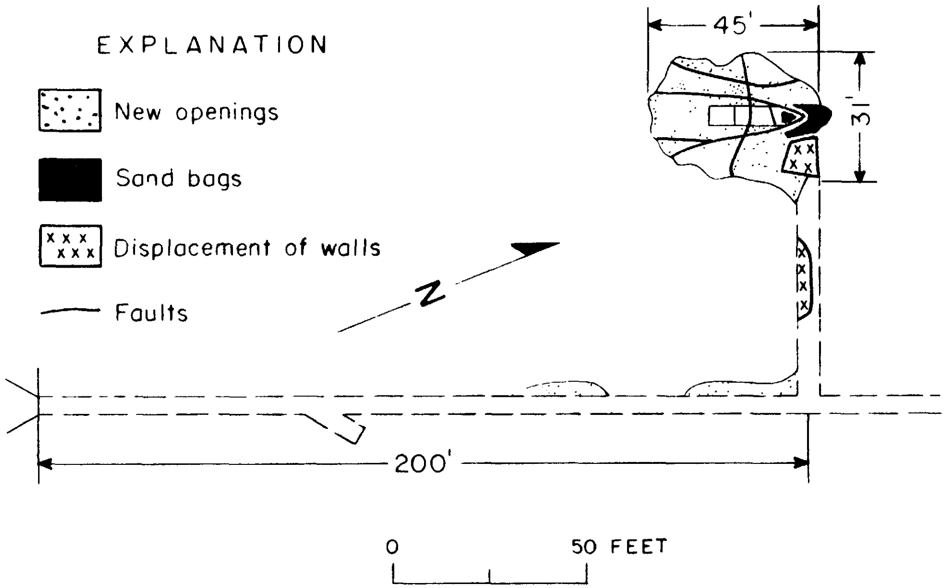



FIGURE 10. UNDERGROUND EFFECT OF 10-TON EXPLOSION, U.S.G.S. TUNNEL

by slickensiding or fluting. The junction plane between the block and the north wall of the lateral was marked by a 4 to 6 inch zone of crushed rubble. This block of rock had originally been the southeast corner of sta. 2+75 W. but had been driven northeastward across the lateral by the explosion.

After the shot, and until excavation had provided evidence to the contrary, it was believed that sandbag stemming in the entrance lateral to Room A had failed and that much of the solid matter in the jet-like cloud driven from the portal an instant after the explosion was provided by the sandbag filling. In later excavation, however, the sandbag stemming was found intact though modified (fig. 10). Subjected to extreme pressures, the material with which the sandbags had been filled--loose, sandsized particles of limestone, quartz grains, and a minor amount of tuff--had been driven together to form a compact, hard, artificial rock. This artificial rock has moderately high strength but when once broken it crumbles into discrete grains. R. E. Wilcox, of the U. S. Geological Survey, studied the material under the petrographic microscope and his report is quoted. "The material in thin section is seen to be about 75 percent limestone fragments of all sizes up to 3 mm. in diameter, the larger ones being rounded. Grain size of the limestone is variable but many pieces are much finer grained on their rims, and interstitial carbonate is likewise very fine grained. The noncarbonate fraction is composed of rock and crystal fragments. Rock fragments are spherulitic obsidian, arkose, and chert. Crystal fragments are quartz, alkali feldspar and plagioclase, all much shattered and strained where in groups, less fractured where isolated in carbonate zones. (Freed from the matrix, most quartz and feldspar crystals disintegrate into tiny fragments upon slight pressure of a needle point under the binocular microscope. Crystals from the raw material source are clear and strong.) It is estimated that there is less than 5 percent of clay mineral present.

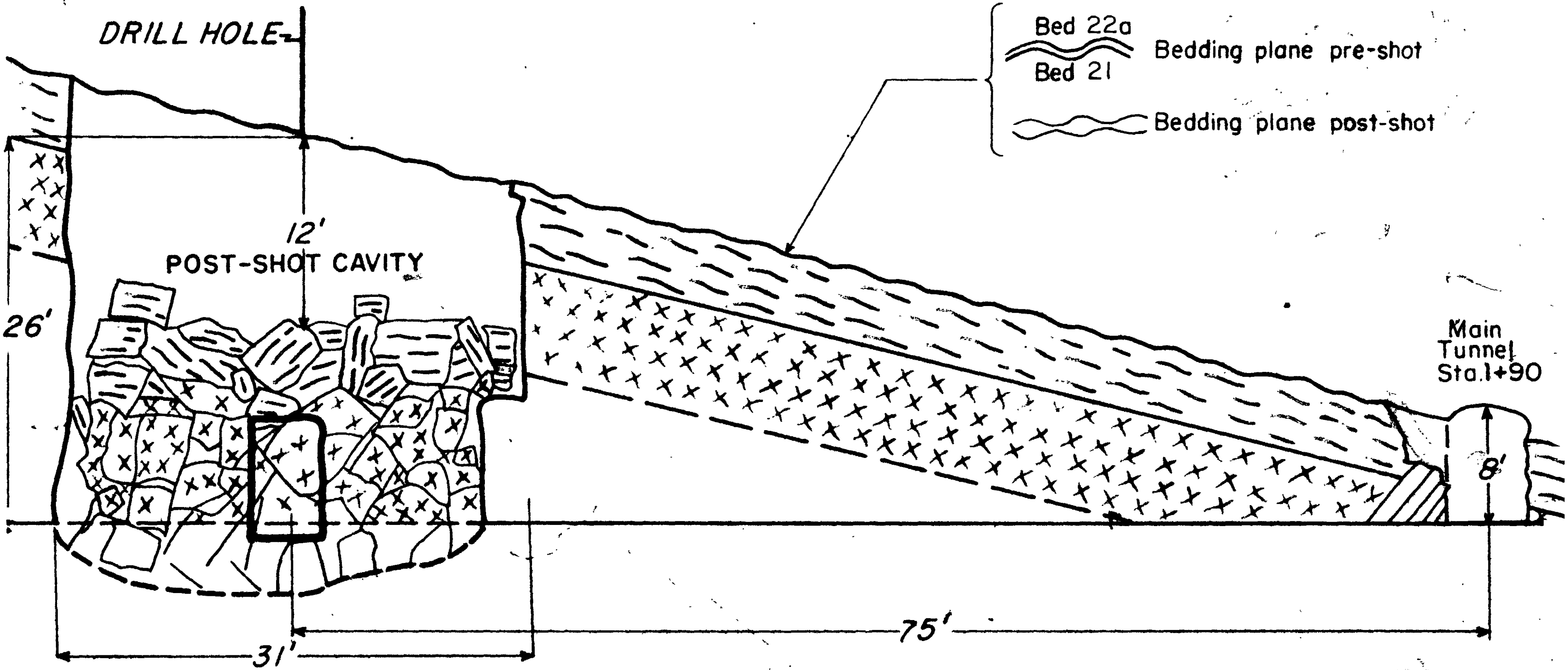
The coherency of this aggregate can probably be ascribed to the compressive granulation and flow of the limestone fragments without fusion. I do not believe the clay fraction was a significant 'bonding' agent here."

Fissures, cracks, crushed zones and renewed movement along old joints in the west lateral and in some parts of the main tunnel are direct resultants of the explosive forces (fig. 7, part B). In the main tunnel the majority of the fractures caused by the explosion were open fissures from less than an inch to 5 inches in width. No damage from the explosion was observed beyond the fault at sta. 2+65 in the main tunnel. In the main tunnel from sta. 1+65 to sta. 2+00, and in the west lateral from sta. 2+00 to sta. 2+16 W. the back of the workings broke out cleanly to the bedding plane between Beds 21 and 22a, and the block above this bedding plane was shifted about 0.8 foot relative to the walls below that plane. In the west lateral from sta. 2+18 W. to sta. 2+40 W., a block of the south wall was moved northward into the lateral. The maximum movement was at sta. 2+23 W. at which point the re-established center line of the pre-shot lateral falls within the post-shot south wall. The eastern boundary of the block was a zone of fractures open about one-fourth to one-half an inch. The western boundary was brecciated but there were very few open fractures. Paralleling and about one foot north of the center line along this block the back of the lateral comes to a steep peak with the rock along this peaked area minutely fractured.

The explosion opened Room A from the original 5x8x8 feet to a roughly rectangular chamber--maximum dimensions 45 feet long, 31 feet wide, and 26 feet high above the original grade line (fig. 10). The volume of this chamber is approximately 1,100 cubic yards of which slightly over half was filled with muck. Later excavation of the north end of the chamber proved by the order in which the different rock types were stacked from grade upward that this muck fell out of the back after the explosion had formed a cavity (fig. 11).

The walls of the post-shot chamber are almost vertical though somewhat irregular in plan view (fig. 10). The back of the chamber is formed by the bedding plane between Bed 21 and 22a previously mentioned in the section on Geology as resembling a ripple marked surface (fig. 11).

The back of the post-shot chamber was faulted and fissured by the explosion. Three north-northeast trending faults in the back, one on the east and two on the west, bound a triangular mass of rock that was driven upward like a wedge. The fault on the east of this triangular block has maximum displacement of 2.5 feet; the two on the west have maximum displacement of 0.7 foot. The displacements on these faults diminish rapidly at the walls of the chamber. A fissure, open 3 to 5 inches, crosses the center of the back from east to west. In the east wall a vertical open fissure is offset about two feet north of the alignment of the fissure in the back, and in the west wall a similar fissure is




CROSS SECTION THROUGH POST-SHOT CAVITY.
Figure 11, 10-TON EXPLOSION

seven feet south of the alignment. These offsets between fissures in the walls and back are more evidence of the independent action of the block above Bed 21.

All evidence, both underground and surface, indicates that the bedding plane between Beds 21 and 22a was a major zone of weakness with respect to both shock waves and gas pressures generated by the explosion. A large block of rocks between this bedding plane and the surface was raised and slightly shifted by the explosion. As described in Part I of this report, the approximate surface boundaries of the block are the fault above Room B, the outcrop of the bedding plane near the portal, and the fault that follows Portal Draw to a point nearly over Room A. Within the tunnel at sta. 2+00, in the back of the explosion Chamber A, and in the cliff above the tunnel portal the ripple marks along this horizon are displaced so that some of the troughs of the overlying Bed 22a rest on the crests of the marks on Bed 21 (see fig. 11). In the southwest wall at sta. 2+00 the upper 1.5 feet of Bed 21 was fractured and spalled. These fractures dip 55° eastward and are fluted or slickensided in direction of dip. Immediately below these east dipping fractures, other fractures dip 65° westward. The angle between the two sets of fractures agrees with the angle produced by breakage of rock under compressive stress, indicating the fractures were formed by the weight of the uplifted block as it dropped back after the explosion.

The disposition of the rock that originally filled the explosion chamber is only partially known. With due consideration for the fact that broken rock occupies about 1-1/3 times the volume it occupied before breakage, the explosion chamber less the volume of original Room A must have contributed about 1,400 cubic yards of broken rock. Of this amount 800 cubic yards can be accounted for--about 600 cubic yards remained in the lower part of the chamber and about 200 cubic yards were distributed along the main tunnel. (Part of this latter material originated in the tunnel.) The jet-like dust cloud that issued from the portal carried out an unknown, but almost certainly minor, amount of material. Thus, approximately 600 cubic yards are unaccounted for.

On the theory that the loss might be attributable to compression of the wall rocks, with consequent decrease in pore space and increase in specific gravity, two pairs of samples were taken from recognizable lithologic horizons. One sample from each pair came from close to the chamber, the other from the same horizon at a considerable distance. The specific gravities of these samples were as follows:

| Sample | Adjacent | Distant |
|---|---|---|
| 1 | 1.40 | 1.356 |
| 2 | 1.69 | 1.78 |

If these results can be considered diagnostic, volumetric decrease in some lithologic units would tend to be canceled out by increase in other lithologic units. Doming of the beds over the chamber cannot account for the missing 600 cubic yards for reference points (lithology, bedding planes, joints, core drill holes) indicate that the walls and back of the chamber are still close to their original position. Moreover, fissures opened by the explosion are not muck filled, but tend to be open--a fact that will account for the permanent updoming of the surface.

## 50-ton Explosion

The second large explosion took place at 6:30:31 a.m. on April 5, 1957, when 50 tons of 60 percent nitroglycerin gelatin dynamite was exploded in Room B. The vertical cover over this room was 174.1 feet but the minimum distance to the surface was 165 feet.

In the 10-ton explosion the dust cloud blown from the portal had led to the erroneous conclusion that the stemming had failed. To insure that the second explosion was completely confined many suggested methods of stemming were considered. Steel blast doors or a massive concrete plug in the tunnel could have been constructed to withstand the theoretical pressure expected. However, such devices would have greater strength than the enclosing rock to which they were anchored and the possibility was good that they would be bypassed. After consulting with the Bureau of Mines the decision was reached that the most effective stemming material was moist clay in bags. The tunnel was to be compartmented with barricades of clay bags alternating with dead air chambers. The reasoning behind this was that a clay-bag barricade , not being rigid, would be driven into any constriction in the tunnel in the manner of a somewhat plastic plug. The alternation of air chambers with barricades is known to be an effective method of absorbing explosive forces.

The 50 tons of dynamite did not completely fill Room B so the surplus space in the room and about 3 feet of the lateral at the entrance of the room were stemmed to insure the highest order detonation possible (fig. 8). The east lateral to Room B was stemmed from sta. 3+52 to the corner at sta. 3+05. The main tunnel was stemmed from sta. 2+80 to 2+60, sta. 2+38 to 2+18, and sta. 0+52 to 0+32.

The explosion of the 50 tons of dynamite fractured, fissured, and displaced the surface of the hill over the shot point. The triangular disturbed area, described in Part I of this report, is about 12,000 square yards in area lying east, south, and west of the point directly above Room B. Even outside of this strongly disturbed area, steep faces of rock such as that above the portal spalled and caved.

In the tunnel the first two clay-bag barricades, between sta. 0+32 and 0+52 and between 2+18 and 2+38, were undisturbed except for falls of rock from the back. In the vicinity of sta. 2+00 the tunnel was enlarged by spalling of the east wall, and fissures 2 to 6 inches wide and too deep to measure were opened in the back (fig. 7, part C). Between the second and third barricade the tunnel was completely blocked. For about the first 5 feet this blockage consisted of large broken rock, but beyond sta. 2+43 the muck and the rock in the walls was minutely fractured. This is the zone along the footwall of the major fault that crosses the tunnel. The rocks in this fault zone were considered to be too brecciated to distinguish features in the original mapping; the effects of the explosion, however, carried the brecciation to a still finer stage. No post-explosion movement was discernible along the fault plane proper.

The third barricade in the footwall of the fault block, between sta. 2+60 and 2+80, was squeezed and twisted. This distortion was not the result of the direct forces of the explosion but resulted from closing up of the tunnel by movement of the walls, floor, and back. The upper part of the tunnel was pushed westward more than the lower part so that the outline of the tunnel was canted where preserved (fig. 12). Between sta. 2+67 and 2+84 the upper part of the tunnel was in a moderately strong, fine grained, bed of red tuff, but the lower part of the tunnel was in a gray tuff grit composed of one-fourth to one-half inch fragments in a fine clay-like matrix. This bed of grit had deformed like a plastic, and, in respect to the walls above, had squeezed inward from both east and west (fig. 12). The back was minutely fractured; and the floor, which had been brought up to grade by filling with muck prior to the blast, was raised as much as 1.5 feet above grade.

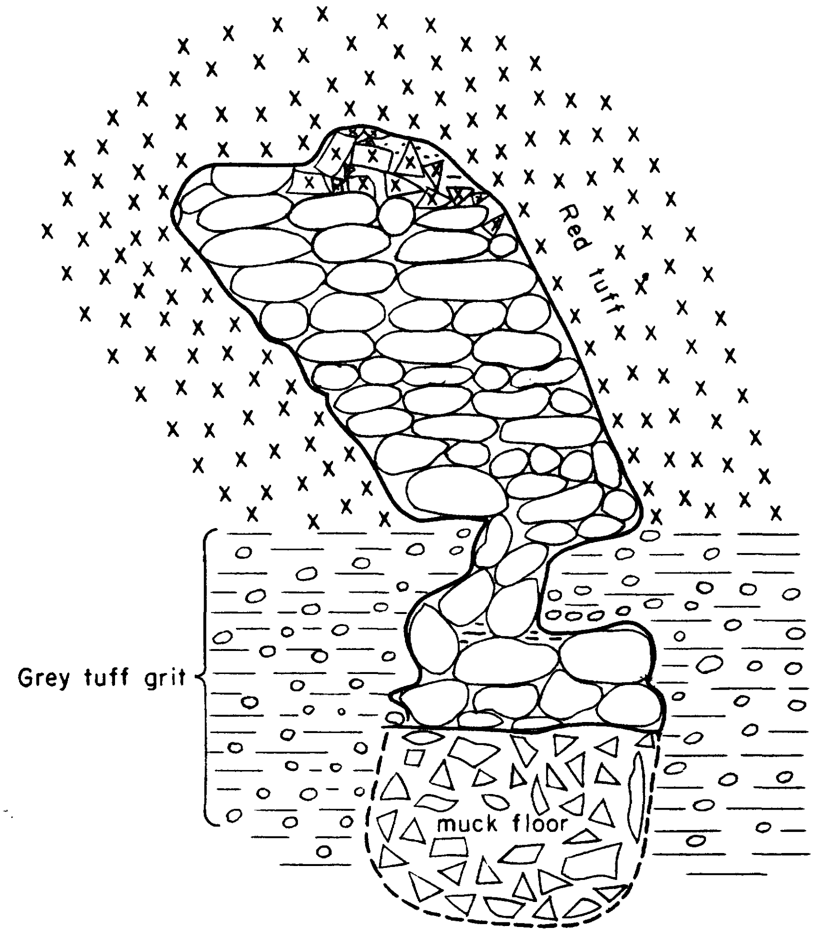



FIGURE 12. CANTED OUTLINE OF TUNNEL, STATION 2+67 TO 2+84

The barricade between sta. 3+05 and sta. 3+52 had been expected to be tightly compressed by direct force of the air blast. When post-explosion excavation reached the corner at sta. 3+05, a strong draft of air circulated through the tunnel and into openings in and around the barricade. The direction of this air circulation changed with atmospheric conditions--blowing inward from the portal toward the explosion chamber when the wind was from the south, and from the barricade toward the tunnel portal when the wind was from the west or north. This, of course, means that openings exist from sta. 3+05 to the explosion chamber and the surface.

In construction of the tunnel, a station for a tugger had been excavated in the west wall of the main tunnel at sta. 3+05. When constructed this tugger station was aligned along the center line of the east lateral (fig. 7, part C); after the blast it had been shifted about 2 feet north of the alignment.

As a means of establishing relative movement of different parts of the tunnel a series of steel rods 30 inches long had been set in pairs--one in the back directly over one in the floor. The following table shows pre-shot and post-shot positions of the reference points recovered:

| Pre-shot | | Post-shot | | | |
|---|---|---|---|---|---|
| Sta. | | Floor | | Back | |
| 0+99.8 | 0.25 ft. W. Cl* | | | | |
| 2+01.8 | on Cl | | | | |
| 2+32 | on Cl | 2+30.63 | 0.33 ft. W. Cl | 2+29 | 0.65 ft. W. Cl |
| 2+71.8 | on Cl | 2+70.6 | ? | Twisted | 2.3 ft. W. Cl |
| 3+05 | on Cl | | | 3+03.7 | 2.4 ft. W. Cl |
| 4+30 | on Cl | | | | |

In addition, a point above the bedding plane between Bed 21 and Bed 22a at sta. 1+78 (not shown on fig. 7) moved 2.2 feet south and 0.5 feet west in relation to a point in the wall below that bedding plane. At the northwest corner of sta. 2+00 the roof block above Bed 21 moved 3.1 feet southwest; again the block above Bed 21 that was raised and shifted in the 10-ton explosion was shifted farther in the 50-ton explosion.

A post-shot resurvey of the center line of the main tunnel falls within the east tunnel wall from sta. 2+44 to 2+82, and the center line of the east lateral falls along the north edge of the barricade at sta. 3+05 (see fig. 7, part C).

In preference to cleaning out the old east lateral, the main tunnel was extended northward to sta. 3+23 north and a new lateral driven eastward in an effort to intersect the explosion chamber (fig. 7, part C). The rock in this new ground was found to be firm and very little disturbed. Fifty-eight feet east of the turn at sta. 3+23 north the new lateral reached broken ground and at 62 feet east of sta. 3+23 it broke into the explosion chamber (face 1, fig. 7, part C). This chamber is tightly filled with a rubble of broken rock. Two or three faces of many of the larger blocks are slickensided by the explosion. In one block a slickensided face cuts another

*Cl denotes center line.

slickensided face approximately at right angles indicating two stages and directions of movement. A block of red tuff, 6x6x14 feet, from the Portal Bed, was about 20 feet below its original stratigraphic position. Blocks of rock a number of feet across were driven into the wall or into other rocks. The dangerous conditions forced abandonment of any additional work in the explosion chamber.

At a point 40 feet east of sta. 3+23 north in the new lateral a short drift was driven southward. This drift cut the north wall of the old lateral but it had been moved 6.5 feet south of its originally surveyed position (face 2, fig. 7, part C). An open space, 1.5 feet wide, 5 feet high, and at least 7 feet deep, was between the north wall and the clay bags. The clay bags were blackened by powder smoke and fly rock fragments were driven into them, but they did not show signs of great compression.

Two raises were put up from the new east lateral, raise I at sta. 0+40 northeast, raise II at sta. 3+23 north (see fig. 7, part C). Raise I encountered a rubble of broken rock 12 feet above grade; raise II encountered similar material at about 30 feet. Indications were that this rubble was not merely on a plane along which the rock had been broken by shattering but really represented the base of a large mass of broken and displaced rock. Judging from the position and height of the raises the base of the broken rock should dip about $30^{\circ}$ toward the explosion chamber. If this were true the contact between broken and undisturbed rock should appear in the explosion chamber at the floor of the new east lateral at face I; this it does not do. It seems probable that the zone of brecciation was controlled by bedding planes to some extent, following a bedding plane for a distance then breaking upward step-like across bedding to a higher plane.

The amount and direction of movement and fracturing underground cannot be measured or evaluated by simple calculations. The workings accessible to observation clearly show that large quantities of rock moved en masse away from the shot point. Within the mass, movements were differential from one point to another. Fairly well substantiated observations might be summarized as follows: the rock in the area close to the explosion chamber or along zones of weakness at greater distances was minutely fractured. These are zones in which the forces of the explosion transmitted into the rock exceed the compressive strength of the rock, the mineral grains are crushed and telescoped together. The zones of minutely fractured material in the main tunnel are along pre-established planes of weakness, but they may also mark the boundary of a body that moved en masse. Open fractures exist mainly outside of the zone of compressive breakage. Here the transmitted compressive forces were less than the compressive strength of the rock. In such situations, the compressive forces at the instant of the explosion do displace the rock outward, but there is little or no fracturing. Upon rebound the tensile strength of the rock is exceeded and open fractures result. The lifting of a block, such as that above the bedding plane between Bed 21 and Bed 22a, may result from a combination of shock wave and gas pressure.

## Tests for Containment of Small Charges of Explosives

A series of tests were conducted to determine the amount of rock cover necessary to completely contain various weights of explosives at shallow depths. The breaking power of 40 percent dynamite on the volcanic tuffs was also compared to 60 percent dynamite. Another series of somewhat similar tests using larger charges and in which seismic velocities and other effects were also measured, will be reported separately by others.

A series of holes, 2 inches in diameter, were drilled from 2.5 to 8 feet deep in rocks similar to those in the USGS tunnel. An amount of dynamite estimated for complete containment at the depth of the first hole was tamped, stemmed, with moist clay or concrete, and fired. If the effects of the charge were contained the amount of dynamite used was increased in new holes of the same depth until the amount necessary to break the surface was found. If the first charge was too heavy the amount was decreased until the effects were contained.

The surface effects of these explosions fell into four categories:

1) No surface effects on rocks. One such hole was excavated. The area around the charge had been expanded so that the hole was 2 to 3 times its original diameter. The rock for a distance of about a foot surrounding this expanded hole was minutely fractured.

2) Incipient fracturing. Hair line cracks develop along planes of weakness such as joints or bedding planes, but there is no displacement of blocks.

3) Fracturing. A definite pattern of open fractures develop, but few blocks are out of place or jumbled. Doming of the surface over the shot point is apparent. Bordering fractures in general dip in toward the shot point.

4) Cratering. A funnel-shaped crater develops, with broken material removed by force of the explosion. The depth and width of the crater has a direct relation to the force of the explosion.

In exact terminology the first two of the above categories are considered as contained explosions. The third category, in which the rocks are fractured does not represent true containment, for openings from the shot chamber to the surface will permit the escape of fumes.

In these tests with smaller charges of explosives, as well as in calculations for the larger explosions, the formula $D = k \sqrt[3]{W}$ (where D = depth in feet, k = constant, W = weight of explosive in pounds) was used as a basis for computation. The limitations of such a formula should be recognized. The constant k is a summation of such factors as the specific gravity, compressive and tensile strength of the various rocks effected, cracks and joints, faces to which the explosion breaks, interfaces or layering of the rock that reflect the shock waves, speed of transmission of shock wave, type of explosive and the speed of propagation. Many of these factors, as well as the interaction between factors, are unknowns or variables. Thus it appears dangerous to consider a value for k that is derived from a series of tests as applicable to another site even under apparently similar conditions.

In these tests at the USGS site the holes in which there was incipient fracturing gave a range in the value of k from 2.5 to 3.6 with the average 2.9 for 60 percent dynamite. For 40 percent dynamite the range was 2.3 to 2.66 with the average 2.49. Moreover, by tabulating the test results by depth of hole the numerical value of k was seen to have increased with the depth of the test hole. With 60 percent dynamite the average value of k for holes from 2.5 to 4 feet was 2.7; holes 4 to 6 feet--2.8; holes 6 to 8 feet--3.3 (higher numerical values of k result in increased depth of rock cover necessary for containment). This indicates that the formula cannot be used satisfactorily without increasing the value of k with increased depth. That is, k is a variable "constant".

It is well known that in some rocks dynamites of lower percent nitroglycerin will break more rock than will higher percent dynamites. Some insight into this was gained from these tests. When the explosion was contained the necessary thickness of cover was less for 40 percent that it was for 60 percent dynamite, but when the force of the explosion exceeded the depth of containment the broken area was greater for 40 than for 60 percent.

In the classification of explosions by the surface effects, the 10-ton and the 50-ton explosions at the USGS site cannot be considered as contained explosions: the 10-ton shot should be placed as intermediate between incipient and fractured. The 50-ton shot should be considered as fractured. In a number of the small test shots the surface effects almost duplicated, at a smaller scale, the results of the larger shots. By correlating the k factor of these test holes with the k factor of holes of equivalent depth that were truly contained and adjusting empirically for the increased depth of the larger shots, the author believes that the k factor for containment of the 10-ton shot should be 3.7. This means that a minimum cover of 100 feet would have been required for complete containment. Similarly, the k factor for the 50-ton shot should be 4.2, requiring a minimum cover of 195 feet for complete containment.