GEOLOGICAL COVERING MATERIALS FOR DEEP UNDERGROUND INSTALLATIONS

S. M. Genensky
R. L. Loofbourrow

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SUMMARY

This report examines twelve different geological configurations, illustrated by as many selected areas of the United States, which might provide desirable sites for large underground installations. A primary consideration is the ability of such a configuration to attenuate appreciably blast waves generated by the ground burst of a nuclear weapon.

Results indicate that the overburden — i.e., the material which lies between the roof of the installation and the surface of the earth — need not necessarily be composed of hard, competent rock. Broken rock, shale, and other uncompacted rock may be more effective as blast-wave attenuators.

A method is suggested for providing protection in the high-frequency range to an underground structure, in addition to that already provided by the natural overburden.
1. INTRODUCTION

It has become increasingly evident that in the event of a sudden attack upon the United States, vital command and control centers must have a high probability of survival to muster an effective counterblow against the attacker. The mere survival of such centers, however, will not guarantee that an effective counterstrike can or will be delivered, for if the lines of communication leading to or from these installations are destroyed, or if the men and equipment required to carry out the counterblow are wiped out, then these centers will be useless. It is not our purpose here to enter into a discourse on the necessity of protecting all the elements that are needed to ensure an effective second-strike capability. We are interested only in the problem of protecting the command centers themselves.

In the event of a surface burst, a multimegaton bomb will develop a crater several hundred feet deep; hence, a vital installation should lie below any region of possible cratering if a high probability exists of its being subjected to a direct hit. Furthermore, such a weapon will develop enormous overpressures that, if not appreciably attenuated, would seriously damage or completely destroy an underground center. Because the deformation of nearly all rocks and soils is governed by stress relationships differing from those of
classical or even finite elasticity, such materials can be expected to dissipate some blast-wave energy, though the rate at which this dissipation occurs is as yet unknown. Therefore, although the decision to confine attention to installations at depths of 1000 ft. or more was based on (1) available information concerning the dimensions of the zones of cratering and rupture as a function of bomb yield [1] and (2) the recognition that most rocks and soils are dissipative media, that decision must still be regarded as somewhat arbitrary. Moreover, we were not convinced that the best way to protect a command center from blast damage was to place it in and under a large mass of hard, competent rock, i.e., rock possessing great flexural and compressive strength.

For these reasons we decided to examine the following question: Among the better known geological arrangements found in nature, are there some that would combine advantages in actual construction as well as possess the ability to attenuate appreciably the blast waves generated by the ground burst of a nuclear weapon? In order to gain some insight into the answer to this question, we compiled a list of geological configurations that might combine these two advantages. After further study and consultation with colleagues at RAND and elsewhere, the list underwent
considerable revision. A search was then made to find actual examples of each of the selected geological arrangements. (Figure 1 shows the areas examined in the course of this study.) The results are reported in Sections 2 through 4, and 6 through 13 below.

On balance, some of the particular regions investigated failed to provide satisfactory loci for a subterranean command center. This should not be construed to mean that the corresponding geological configurations are unworthy of further consideration. The authors do not claim to have discovered and examined all the geological arrangements that might be used to dampen nuclear-generated blast waves. Nevertheless, those that were examined encompass a rather broad range of geological materials, many of which are common to large portions of the United States.

Section 5 is devoted to discussing a possible method of providing protection to an underground installation in addition to that already supplied by the natural overburden.

It must be emphasized that without further experimental evidence it is impossible to draw definite conclusions as to how various combinations of rock will react to a nuclear blast. Unfortunately, the extrapolation of results obtained from experiments using high explosives to the nuclear domain is very questionable, because much of the phenomenology associated with a nuclear blast differs radically from that involved in conventional high explosives; e.g., for some rocks and nearly
Fig. 1 — Geographical areas investigated for possible installation sites

1. Prince William Sound and The Kenai Peninsula
2. Southwestern Minnesota
3. Santa Barbara County, California
4. Keweenaw Peninsula, Upper Michigan
5. Cornwall, Pennsylvania area
6. Vermilion Cliffs, Mojave County, Arizona
7. Grand Wash Cliffs, Mojave County, Arizona
8. Barberton, Ohio area
9. Rifle, Colorado area
10. Morgantown, West Virginia
11. McConnelsville, Ohio area
12. Logan County, Illinois
all soils, dissipation of blast-wave energy by mechanisms such as compaction and plastic flow will probably be more significant for a large nuclear burst than for a high explosive.

Finally, the concentration in this report upon the study of geological problems, as well as some excavation and construction problems, related to deep subterranean command centers does not mean that we necessarily consider these problems to be either the most important or the only questions related to the establishment and maintenance of such facilities. An exhaustive study of deep underground installations for military purposes would have to include such external factors as proximity to an existing military base, nearness to population centers, availability and capacity of existing communication channels, and accessibility by various modes of transportation. In addition, the authors have, however, taken into account such internal factors as the size and layout of the center, the size and shape of its tunnels and connecting shafts, methods of sewage disposal, sources of water, methods of heating and air conditioning, and means of supplying power. Nevertheless, we are convinced that an examination of the local geology as to its effect upon the cost and time of construction and its ability appreciably to attenuate blast waves should be given prominent attention in site selection.
2. VALLEY GLACIERS

In the neighborhood both of the Kenai Peninsula and of Prince William Sound in Southern Alaska, numerous valley glaciers terminate at the head of deep fjords that are bounded by steep rocky cliffs composed primarily of sandstone, greywacke, and shale, with minor amounts of conglomerate, volcanic ash, and limestone \([2]\). If an underground installation could be located in competent rock below such glaciers, it would probably enjoy considerable protection from both bomber and missile attacks involving multimegaton weapons. This is because glacial ice acts like a viscoplastic material and hence should be unusually effective as a blast-wave attenuator. This dissipative mechanism will be effective, however, only if the thickness of the glacial cover is large compared to the maximum depth at which cratering may be expected to occur. Furthermore, the upper 100 ft. or so of these glaciers contains a considerable amount of entrained air and hence can be expected to compact under blast loading. In the case of a surface burst, however, this compaction may be of only secondary importance, because multimegaton weapons may develop craters that penetrate to the substratum of airless ice.
Since the glacial fjords are very deep and the large masses of rock that form their margins either drop sharply into the sea or terminate close to the shore (Fig. 2), it should be possible to develop horizontal entrances in the rock from locations that are a safe distance below the glacial tongue.* Further, such entrances must be driven well above the ocean surface in order to prevent flooding due to unusually high tides and exceptionally large waves produced by ice breaking from the seaward end of the glacial tongue. In addition, these entrances would be driven back toward the glacier, and at an appropriate distance above its tongue they would descend to the region in which the installation was to be constructed. Since the rock in this area of Alaska is subject to frequent seismic disturbance, may possess large residual stresses and has been highly folded and faulted, a very careful investigation of the local geology should be undertaken before proceeding with any extensive excavation.

3. MASSES OF PLASTIC ROCK

Except for Sioux quartzite in the very corner of the state, the ancient crystalline rock throughout the southwestern quarter of Minnesota is granite or granitic rock [3]. For the most part, this ancient rock is covered in turn by clay shales dating from the Cretaceous era and by glacial drift.* Where

*The portion of the glacier that fronts on the sea.
Fig. 2—Tiger Glacier

This glacier, one of several projections of the vast Sargent Icefield, is located about 40 miles east of Seward on the northeastern side of the Kenai peninsula. It meets the sea at the head of a long narrow inlet of Prince William Sound called Icy Bay.
the clay is dominant, the covering rocks form a semiplastic mass that in some places is as much as 500 ft. thick (Fig. 3). Further, water-well records [4] indicate that in some areas of considerable extent, this cover contains few aquifers.* Unfortunately, water-well drillers are primarily interested in locating sources of water and not in the study of structural geology. Hence these records are likely to do nothing more than indicate where additional detailed investigations might prove useful. Insofar as these records are confirmed by detailed site appraisal, it should be possible to find places favorable to the construction of an installation where the overburden may be expected to attenuate blast waves generated by nuclear devices at an abnormally high rate. Both the porosity generally exhibited by these clays and their demonstrated ability to attenuate and alter the form of waves resulting from high-energy explosives and seismic disturbances seem to bear out this conjecture. However, the non-linearity of much of the phenomenology of nuclear explosions makes the extrapolation of the results obtained from experimentation with high explosives extremely hazardous.

Since large residual stresses have been observed in some of the granite quarries in central Minnesota, the determination of such stresses should be a critical factor in the appraisal of any site of the type discussed here.

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*Water-bearing beds or strata of earth, sand, gravel, or porous stone.
Fig. 3 — Representative geological column of southwestern Minnesota
About 12 miles west of Wilmar
In addition to glaciated outcrops, there exist non-glaciated outcrops in the area, which exhibit kaolinization* into the granite to depths of as much as 150 ft. This kaolinized granite should have physical properties similar to those of the overlying clays and hence should effectively increase the protective plastic cover.

Because there is little topographic relief in this part of Minnesota, it would be necessary to construct long, inclined entrances. Care should be exercised to avoid excavating them in water-bearing beds of sand and gravel, because these aquifers will exact their price in both time and money. If this is done, it should be possible to construct the entrances using only moderately strong, continuous support** from the surface down to the ancient rock.

It is therefore clear that, before commencing construction in the area, an extensive and well-coordinated program of testing and boring should be carried out to locate sites with overburden that is free from water-bearing beds of sand and gravel, and with ancient rock that is at most only slightly fractured and free from large residual stresses.

*The decomposition of certain rock-forming minerals to form kaolin or similar clays.

**For example, timber or metal lagging between steel arches.
4. CELLULAR ROCK

The Monterey Formation is found throughout much of California's Coast Range. Generally this formation consists of thin-bedded, light-colored shales; in some areas, however, it contains diatoms, the thin-walled siliceous skeletons of microscopic sea plants. Diatomite, the rock formed from the deposition of fossil diatoms, is found in many portions of the United States, though nearly pure diatomite from 500 to 1000 ft. thick is unique to Santa Barbara County, California [5] (see Figs. 4 and 5). Throughout the shaded areas in Fig. 4, the diatomite is 500 or more feet thick and extends to or nearly to the surface, and where it is not exposed it is covered by loose sand or soft porous rock. In most beds the fossil diatoms are mixed with shale, volcanic ash, bentonite, a black variety of opal, and other denser and harder forms of silica. Generally this admixture increases with depth.

Figure 5 illustrates the three vertical sections AA', BB', and CC' in Fig. 4.

Generally in the California Coast Range, the Sisquoc (Tsq) and upper Monterey (Tmu) formations vary considerably in structure and composition. A portion of this variation in the Lompoc area is depicted in the sections shown in Fig. 5, taken from the Dibblee Report [5]. Dibblee describes some of this variation in composition somewhat as follows:

Near the coast, north of the Santa Ynez River at Burton Mesa (the north end of Section AA' and beyond), the uppermost
300 ft. of Sisquoc is composed of nearly pure diatomite. This rests upon 1300 ft. of splintery diatomaceous claystone, which in turn overlays 700 ft. of thin-bedded, porcelaneous platy diatomaceous shale. The upper Monterey is reported to be similar to the lower Sisquoc.

In the Santa Rita Hills, which rise east of the town of Lompoc (east of the northern third of Section CC'), the lowest 750 to 1000 ft. of Sisquoc is reported to be made up of almost pure diatomite. A similar bed has been extensively quarried in the Sisquoc or upper Monterey south of Lompoc.

The Sisquoc and upper Monterey are resistant to erosion and commonly make up the walls of steep-sided gullies and canyons. The lower Monterey (Tml) and the beds immediately beneath it are composed primarily of clay-shale with some limestone and siliceous shale. These lower beds are subject to landslides, and hence it is very unlikely that they would provide desirable loci for underground installations.

Pure diatomite is a soft chalky material with porosity as high as 80 per cent. When dry, it is almost white and its specific gravity is about 1/2. It is so soft that power shovels can remove it without the help of blasting, though occasionally cherty beds are encountered that must be drilled and shot. Interestingly enough, in spite of its softness, small tunnels have been driven through diatomite and the walls of these openings have held up well over the years [6], [7], [8].
When quarried, diatomite is damp but not saturated, though its water content increases with depth until saturation occurs. Nevertheless, water does not flow from, nor is it apt to flow through, fractures in diatomite. In addition, oil, gas, and other harmful substances are not common in these beds. When they do occur, they can be shown to originate in the impure shales.

The low density and high porosity of the diatomaceous cover appears to indicate that if it were subjected to the high overpressures generated by multimegaton bombs, it would undergo considerable compaction. Further, where there is room for lateral motion of the covering material, plastic flow may occur. The combination of these two dissipative mechanisms should greatly reduce the harmful effect of blast waves. In addition, a 1000 ft. bed of diatomite should provide protection against repeated attacks, for the zones of cratering and severe rupture produced by the ground burst of nuclear weapons would affect only the upper portion of the diatomaceous cover.

There is some question as to whether the presence of moisture in the diatomite will be a help or a hazard. Investigations by the U. S. Bureau of Mines have indicated that a rock specimen is a more effective attenuator of acoustical waves when water-saturated than when dry. On the other hand, these experiments were performed under circumstances quite dissimilar to those expected to prevail during a nuclear attack.
Hence it is virtually impossible to extrapolate from the Bureau of Mines tests to the problem at hand.

The boundary between the pure diatomite and the underlying beds is not clearly defined, for, as mentioned earlier, there exists a transitional region in which the percentage of volcanic ash and opalized siliceous shale increases with depth. Generally these rocks are harder than diatomite, and occasionally they may exhibit severe fracturing. Nevertheless, it is believed that suitable loci for subterranean installations can be found in this underlying rock.

In those parts of Santa Barbara County that are rich in diatomite, the terrain is very uneven. Strictly on the assumption that the choice of an installation site depends only on geological considerations, it should be possible to construct entrances with very gentle slopes starting from the base of one of the numerous canyon walls. Furthermore, the moderate strength, absence of weathering, and low permeability of pure diatomite should make shaft driving rather simple.

Currently, mining is being carried on in several quarries that are easily reached and where the diatomite is very pure. This would indicate that such property would be quite expensive. The beds of diatomite are so extensive, however, that it is very likely that suitable locations could be found that do not interfere with current or prospective mining operations.
5. UMBRELLAS

Since much reliance is being placed upon protecting large underground installations from the deleterious effects of multimegaton weapons by merely locating them in competent rock far below the earth's surface, it should be pointed out that in view of the enormous overpressures developed by thermonuclear weapons, such installations might experience serious damage even if they lie below as much as 1000 ft. of cover. Therefore, it might be necessary to provide them with additional protection. One way of doing this might be to make new openings in the rock above these structures. These new openings, which we shall call "umbrellas," should be designed to subtend as large a solid angle relative to the installations as is economically possible. It is hoped that this protective mechanism will be effective against at least the high-frequency components of a nuclear-generated blast wave.

Unfortunately, the unit cost of such umbrellas may be rather high; nevertheless they deserve serious consideration because when properly designed they might provide exceptionally fine protection. For consider what occurs when a blast wave generated by the ground burst of a multimegaton weapon encounters such openings. The disturbance propagates initially as a compressive wave, and upon reaching the roof of the umbrellas, at least its high-frequency components* are

*Those whose wave lengths are small compared to the dimensions of an umbrella opening.
almost entirely reflected and returned toward the earth's surface as a tensile wave. This follows from the expectation that for these high-frequency components, phenomenology depending upon wave length, such as interference and diffraction, is expected to be of only secondary importance, and from the fact that the ratio of the acoustical impedance of rock to that of air is of the order of 10,000. Therefore, only a very small fraction of the blast-wave energy in this frequency range is expected to pass through the umbrellas and continue on toward the installation, though additional energy in this portion of the spectrum may be transmitted through the umbrellas by rock spalled from their roofs. Such spalling is very likely to occur because, although rock is very strong in compression, it is quite weak in tension. This additional energy transfer will, however, be small compared to that which would have taken place if umbrellas had not been constructed. Furthermore, if the umbrellas are located far enough below the ground so that there is no danger of their lying in the zones of cratering and serious rupture, then they can be expected to be equally effective against several nuclear explosions. For although they may contain a considerable amount of broken rock and may be severely fractured after a nuclear attack, they will still encompass about the same amount of void space, and it is the large impedance mismatch between the rock and this void space that is expected to provide a mechanism for successful blast-wave attenuation.
In addition, the construction of umbrellas could mean savings in the cost of excavating the installation and its connections with the surface; for if care is exercised in designing the umbrellas and installation, then the latter could probably be located closer to the surface than if it were devoid of this added protection. Specifically, savings would then result from an acceleration in construction and from a need for shorter connecting shafts and inclines, especially when the installation is located below ground of gentle relief. Furthermore, a closer proximity to the surface would make ingress and egress much more convenient both during the period of construction and during the day-to-day operation of the facility.

Umbrellas could be used also to store equipment and supplies that are needed for the day-to-day operation of the installation but are expendable during and after an attack. Such an application of umbrellas might bring about a reduction in the total floor space required in the underground center.

In any event, even if it is not possible to include umbrellas in the original design of an underground center because of budgetary considerations, they still could be excavated after the installation is completed, without seriously disrupting any of its connections with the surface and perhaps without curtailing any of its operations. In order to do this, (1) the installation must be located in competent rock, (2) it must have from 50 to 100 ft. of sound rock above
it, and (3) this overlying rock must be outside the range of any possible cratering or rupture.

There is some question as to whether umbrellas should be partially filled with broken rock, sand, etc., or whether they should be left completely empty. In some quarters it is felt that the broken material would provide a mechanism for absorbing much of the energy that would otherwise be transferred to the umbrella floors by rock spalled from the ceilings. Another view is that the presence of broken material in the umbrellas will appreciably reduce the impedance mismatch between these openings and the overlying rock, and thus would tend to defeat the primary purpose of creating such openings.

In order to help resolve this doubt, experiments should be performed in the laboratory on models of various umbrella-installation configurations to ascertain how they react to simulated blast waves. In addition, in order to check the validity of the assertion that umbrellas would be effective attenuators of blast waves, it is strongly urged that explosives be detonated in the rock immediately overlying large abandoned stopes. Employing the proper instrumentation, this would permit the measurement of displacement, overpressure, and acceleration at various locations in the neighborhood of such stopes. Further, it would also be possible to examine the effect of (1) introducing supporting pillars into the stopes, (2) varying the amount of broken material in these
openings, and (3) changing the size and location of the explosive charge.

Figure 6 depicts a typical installation protected by a system of umbrellas. At the extremities of the installation these umbrellas are designed to provide protection against blast waves approaching from the side as well as from above. Note that pillars are left between the umbrella openings to provide support. These pillars should be kept as small as possible and should rest upon rock that does not lie directly above any installation opening. If the total pillar cross-section is small compared to that of the entire system of umbrellas, only a small fraction of the energy carried by the high-frequency components of a blast wave may be expected to pass from the umbrellas on to the installation. Unfortunately this is not true for the low-frequency components,* since umbrellas will have no attenuating effect in that frequency range. Should it prove advisable, some or all of the supporting pillars could be designed to fail under large dynamic loads.

6. EXISTING MINES

With few exceptions, it is imprudent to count upon using mined openings as loci for large underground installations,** for mining companies are primarily interested in economically extracting as much ore as possible from their property.

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*Those having wave lengths that are large compared to the dimensions of an umbrella opening.

**One such exception is cited in Sec. 9.
Fig. 6—Diagramatic cross section showing "Umbrellas"
As a result, mines are apt to be worked very close to the limits of safety based on considerations of static equilibrium. Thus, it is not uncommon to find evidence of severe cracking and fracturing in the head-wall rock and supporting pillars. Such deterioration makes these mines unattractive as installation sites, for if they were subjected to the large dynamic loads generated by thermonuclear devices, they would certainly suffer severe damage.

On the other hand, suppose it were possible to find abandoned or almost depleted mines with the following properties: (1) The ore occurs in many, almost horizontal, overlapping beds most of which are below 500 ft. and each of which covers a large planar area (of the order of several square miles). (2) Each mined bed has been thoroughly worked and the resulting openings are essentially randomly spaced with respect to those of the other mined beds. (3) There exists a thick layer of competent rock below the existing mined openings. (4) The mines are free of poisonous and highly flammable gases. (5) The openings are dry or require only nominal pumping to keep them dry. (6) The use or purchase of the property could be obtained for a reasonable price. If these conditions could be satisfied then an installation placed at least 50 ft. below the mined openings would probably enjoy unusually fine protection from blast waves produced by nuclear weapons, since as in the case of umbrellas, the existing workings might be expected to reduce appreciably the danger of blast
damage. Admittedly, the mined openings would suffer serious damage as a result of severe spalling, but since the percentage of voids is not expected to be reduced by a nuclear explosion except within the cratering zone itself, these workings should be equally effective against a series of attacks.

Unfortunately, the occurrence of even two thoroughly worked and overlapping lodes at great depth is very uncommon in this country. Nevertheless, the mining areas that are extant deserve careful consideration since they would very likely provide significantly more protection to an installation than if it were placed at the same depth in similar rock in a mine-free area. Examples of two overlapping, mined-out lodes at great depth are found on the Keweenaw Peninsula of Northern Michigan. There, copper ore is found in certain beds of a thick, hard, rather uniform sequence of basaltic lava flows.* The inclination of the mined layers varies from mine to mine, from about 35° to 60°. At depth these ore beds tend to be less inclined, but this tendency is not significant within 3000 ft. of the surface. In general, the ore is richer and thinner (4 to 5 ft.) near the surface and becomes progressively leaner and thicker (15 to 20 ft.) at vertical depths of a mile or more.

The mean annual surface temperature in this area is 42°F. According to the U. S. Geological Survey, the temperature

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*See reference [9], Groups 6.1 – 6.3 and 10.1a – 10.5d.
gradient in these copper mines is about 0.01°F per foot, which is unusually low. This implies that rock temperatures of about 60°F and 70°F can be expected at depths of 2000 and 3000 ft., respectively.

Mining has not been uniform over the central portion of this mineralized belt; nevertheless, the minable areas are very extensive and rather uniform. Further, both the rocks and ore are remarkably competent. This has resulted in a series of "open-stope" mines, each extending 2000 to 3000 ft. horizontally, many as much as 4000 to 6000 ft. down-dip, and a few to 9000 ft., all measured in the plane of the ore. Openings of these dimensions are, of course, not continuous. Access to most of the mines is by means of inclined shafts in ore, many of which are protected by continuous pillars from 100 to 300 ft. wide, measured horizontally. Shafts so protected are usually spaced at intervals of 2000 to 3000 ft. A horizontal pillar as much as 20 ft. wide has been left under many drifts, which follow the contour of the ore; generally they are spaced 100 ft. apart in the plane of the ore. In the richer parts of some mines these pillars have been removed. In leaner sections, the pillars are apt to be larger, and in places irregular pillars have been left between shafts and drifts. These mined openings, and the depths to which they descend, are quite extensive.

There are places where the rock above the ore has been fractured in subsidence. Violent fracturing in the form of
rockbursts has occurred in some mines, but fracturing at less than 3000 ft., measured vertically, is thought to have been gradual and limited in its extent.

The rock in the region is dense and substantially impermeable, but water has entered some of the workings as runoff from the surface and through fractured areas. Recently water was pumped from some long-flooded mines of Calumet and Hecla, Inc., and was found to contain dissolved salts and gases in sufficient quantities to require special pump construction and procedure [10][11].

Probably the most extensive pair of parallel overlapping planal openings in this area is found near Calumet, Michigan. There the Conglomerate (Fig. 7) and Osceola (Fig. 8) lodes dip at an angle of approximately 35° and are separated by 440 ft. of sound rock. Almost 80 to 90 per cent of the Osceola lode has been removed over a horizontal distance of about a mile to an inclined distance of 4700 ft. (about 2800 ft. measured vertically). Nearly all of the overlying Conglomerate lode has been opened over a horizontal distance of about three miles and to more than twice the depth of the Osceola lode.

An installation located in the competent rock below these two lodes would be well protected from severe blast damage. Because of the inclination of the lodes, however, it would be possible for a bomb to strike the surface and generate a blast wave that would reach the installation without intersecting
either opening. In that case, the survival of the installation would depend primarily on the dissipative properties of the intervening rock and the spherical expansion of the blast wave. Therefore, it might prove necessary to construct "wrap-around umbrellas" (Fig. 9) to provide additional protection against this contingency.

If existing shafts were utilized during the construction period, work could be advanced by as much as a year. In many cases entrances are larger than those of most metal mine workings and hence they could serve as passageways for all construction materials and equipment. It appears advisable, however, to construct new sloping entrances for permanent use that are entirely independent of the present openings, because there is a high probability that the present openings would suffer serious damage or even complete collapse under large dynamic loading. In any event, the new entrances need not be as large as the present openings and hence would be more resistant and less costly.

7. CAVED ROCK OVER A MINED MASS

Near Cornwall, Pennsylvania, a heavily worked iron mine (Fig. 10) lies below approximately 800 ft. of broken, uncompacted rock, which originally formed the cover over the ore. This covering material is composed of slate, conglomerate, quartzite, and limestone. At the surface the broken material occupies a nearly square region about 2000 ft. on an edge \[ \frac{1}{2} \]. The underside of this broken material is inclined at an angle
Fig. 9 — Vertical section of two overlapping copper mines in northern Michigan
Broken, uncompacted rock resulting from the complete removal of ore that was originally near the bottom of this shattered zone.

Fig. 10 — Cross section of an iron mine near Cornwall, Pennsylvania.
of $30^\circ$ with the horizontal and nearly coincides with the bottom of the ore bed. An installation located under this shattered mass at a depth of 1400 ft. would receive considerable protection, because the broken unconsolidated material should compact under blast loading, and the reflections at the numerous internal surfaces of discontinuity can be expected to provide additional attenuation. Furthermore, since nuclear devices are not expected appreciably to affect the percentage of voids in the overburden, except in those regions in which the rock is fused, the dissipative mechanisms can be expected to be operative under repeated attacks. It is possible, however, for a bomb to strike the ground outside the protective range of the broken mass and hence generate a blast wave that would encounter the installation without first traversing the shattered material. Such a blast wave would have to pass through at least 2000 ft. of rock before reaching the underground center. If this thickness of cover is not sufficient to provide adequate protection to the installation, additional protection could be had by creating artificial openings as described in Sec. 5.

It is unfortunate that the rock that lies 50 to 100 ft. below the ore is fractured and unsuitable for underground construction. This is borne out by the fact that the two existing mine shafts that pass through this relatively unstable material required lining with reinforced concrete. It is possible that more competent rock can be found at greater
depths, but this has yet to be established. Further, it is said that 500 to 1000 gal. of water per min. must be pumped from the mine, and presumably this dewatering would have to continue throughout the life of any installation located below these workings. Finally, the extent to which the mine has been depleted has not been fully ascertained, and hence the value of the property is not known.

8. GREAT THICKNESSES OF CELLULAR ROCK, I

In the area of the Vermilion Cliffs and the Grand Wash of Northwestern Arizona (Fig. 11), it is likely that there is cover consisting in the main of cellular rock that is about 2500 ft. thick [13][14]. Although no record of the rocks in this region could be found, it is expected that except for the limestones in the Grand Wash they all should be moderately porous and should appreciably attenuate acoustical waves.

From an examination of outcrops of similar formations in the region, it is inferred that a thick, nearly horizontal bed of Kaibab limestone underlies the Vermilion Cliffs and that a mass of granite supports those of the Grand Wash. Both the limestone and granite are probably capable of supporting a large installation. Since little detailed information is available concerning the geology of these regions, they should be explored to ascertain the distribution and physical properties of their rock before any extensive excavation is undertaken. Should such an exploration yield favorable
Fig. 11—Representative geological cross sections of the Grand Wash Cliffs and the Vermilion Cliffs
Mojave County, Arizona
results, sites should then be sought where rivers approach the steep cliffs below the beds of shale, so that horizontal entrances can be constructed in competent rock. This would mean savings in both time and money, because running entrances through the soft, weak shales would require the use of continuous, moderately strong support.

3. GREAT THICKNESSES OF CELLULAR ROCK, II

Near Barberton, Ohio, below 200 ft. of glacial drift, sandstone, and shale, lies 1950 ft. of a firm but relatively unstable shale* (Fig. 12). It is expected that this shale will prove to be impermeable, because no water from surface reservoirs has entered either shafts cut through the shale or the mine excavated in the limestone below it [15]. Further, it is believed that tests will demonstrate that the shale is an effective attenuator of acoustical signals.

Toward the west this vast shale cover decreases in thickness roughly at the rate of 10 ft. per mi. for about 60 mi. From there its thickness remains fairly constant for another 10 or 20 mi. To the north it thins out at the rate of approximately 20 ft. per mi.

Below the shale is an unusually regular layer of hard, strong Columbus limestone.** Observations of the mine mentioned

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*Shafts of moderate size were sunk through this shale using nothing more than light timber supports, but gradual deterioration of the shale surfaces made it necessary to concrete the shafts along their entire length.

**See reference [9], Group 9.1.
Fig. 12 — Geological column at Barberton, Ohio
30 miles south of Cleveland
above indicate that this limestone would provide an excellent locus for an underground center. The mine consists of large rooms carved out of the rock, but it is near a chemical plant and approximately 8 mi. from Akron.

In the event that it is decided to use the mine, it might prove advisable to construct new, gently sloping entrances to achieve greater dispersion of the means of access. Such entrances would have to be quite long and would very likely require lining with concrete over a portion of their length.

11. GREAT THICKNESSES OF CELLULAR AND THIN-BEDDED ROCK

The Book Cliffs near Rifle, Colorado, are composed of from 2000 to 3000 ft. of a marlstone known for its excellence as an attenuator of acoustical signals (Fig. 13). Outcrops of this rock exhibit from 10 to 30 color variations per ft. These thin layers are probably composed of rocks that differ appreciably in porosity and kerogen content. Thus it is highly likely that this multilayered mass will dampen out the high-frequency components of bomb-generated blast waves, and this will result in a smoother wave form that is less likely to produce serious spalling from the roof and walls of an installation.

No information is available concerning the unexposed rock at the base of these cliffs. Should it resemble the rock in the upper strata [18],* it would provide an excellent

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*See reference [9], Groups 25.2 and 25.2a; reference [16], Groups 29.1 – 29.9; reference [17], Groups 41.2 – 41.4.
Fig. 13—Representative geological cross section of the Book Cliffs near Rifle, Colorado.
location for an underground command center. Horizontal entrances could probably be driven in the face of the cliffs. Since such entrances must pass through a talus slope, they would require support near the portals.

11. MINED OPENINGS COMBINED WITH CELLULAR AND THIN-BEDDED ROCK

Near Morgantown, West Virginia, the Monongahela Formation, which lies above the Pittsburgh coal seam, is composed of some 23 members [19], including 8 sandstones and shales,* 5 thin-bedded limestones together with a considerable amount of shale especially along the parting planes between layers, and 7 coal horizons together with their underclays. The upper Conemaugh Formation, which lies below the Pittsburgh coal seam, is similar to the Monogahela Formation but contains much less limestone. Both the Pittsburgh seam and the Sewickley seam, which lies about 100 ft. closer to the surface, have been mined extensively in the Morgantown area (Fig. 14).

If it were possible to locate a region of at least 1000 ft. square where (1) the Pittsburgh and Sewickley seams have been thoroughly mined without leaving any large solid pillars, (2) the openings in each seam are not so large that complete closure has occurred, (3) there exists at least 300 ft. of cover between the Sewickley seam and the surface, and, (4) each seam is free of large accumulations of water, then it might be feasible to construct an installation in the sandstone or

*See reference [17], Groups 26.1a – 26.4b.
Fig. 14 — Representative geological cross section and column, near Morgantown, West Virginia
siltstone below the Pittsburgh seam. If condition (4) cannot be satisfied, then arrangements would have to be made for continuous pumping. An installation in this environment would be protected by both the opened coal seams and the many dissimilar rock beds, most of which are cellular.

The coal seams that closely approximate "umbrellas" and the numerous members of the Monongahela and Conemaugh Formations would probably eliminate at least the high-frequency components of an approaching blast wave.

The rock of the Sewickley seam is generally strong, but its underclay is soft and fairly thick. This has led to closure due to stress relaxation in the footwall rock in those portions of this mine where all the ore has been removed except that which was left in the form of pillars. Rooms that originally were from four to five feet high are now from one to three feet in height.

As for the Pittsburgh seam, its roof is only in fair condition and there are indications that it has failed in many places. Portions of the mine floor are very hard, and in those areas the pillars should provide some support, even though they are expected to be partially shattered. Where the floor is soft, stress relaxation like that in the Sewickley mine is assumed to have occurred [20] [21] [22].

Unfortunately the Pennsylvanian System, which includes both the Conemaugh and Monongahela Formations, is characterized
by large variations in the thickness, competence, and composition of its constituent rocks. This makes it imperative that a careful program of testing and boring be carried out before any construction is undertaken in this region.

Should a suitable site be found, it would be possible to reach it by gently sloping shafts. It is very unlikely, however, that all the constraints listed above can be satisfied in this area.

12. THIN-BEDDED CELLULAR AND PLASTIC ROCKS, I

Near McConnelsville, Ohio, large numbers of thin sedimentary beds of the Pennsylvanian System are found between Zanesville and Marietta. Here the Pennsylvanian System is divided into four formations, The Monongahela, Conemaugh, Allegheny, and Pottsville [19] [23] (Fig. 15). As in the neighborhood of Morgantown, West Virginia, the Monongahela Formation contains 23 members, including 8 coal horizons, 5 limestones with many shaley partings, and 9 shales and sandstones.* In each coal seam the thickness of the ore varies considerably from place to place, but the thickness and occurrence of the accompanying underclays is much more uniform. The Conemaugh Formation consists of 57 members, including sandstones, shales, 13 limestones, and 12 coal horizons. In some places, some of the sandstones are as much as 30 ft. thick, but thicknesses of 2 to 10 ft. are much more common. The Allegheny Formation

*See reference [17], Groups 26.1a – 26.4b.
Fig. 15—Representative geological cross section near McConnelsville, Ohio, between Marietta and Zanesville.
contains 40 members,* including 13 coal horizons** [25], and
the Pottsville Formation exhibits 55 members, of which 12 are
coal horizons. In other respects these latter two formations
are similar to the Conemaugh Formation.

The rocks that make up the Pennsylvanian System, with
the exception of a few limestones, are believed to be quite
porous. Some of the sandstone and limestone beds are quite
hard and show evidence of fracturing, while the shales and
shaley partings separating these beds are generally soft
and unbroken.

The entire Pennsylvanian System is about 1100 ft. thick
and is made up of 175 recognizable members. Some of these,
such as the "massive" sandstones, may consist of as few as
2 or 3 distinct beds, but most of the other sandstones and
probably all of the shales and limestones are composed of from
10 to 30 beds, which may be of similar composition even though
physically separated from one another. Thus a blast wave
penetrating this covering would encounter from 1000 to 2000
interfaces between rocks of differing physical properties.
Such a "sandwich" of material should appreciably attenuate at
least the high-frequency components of a blast wave.

The thickness of the Pennsylvanian System is by no means
uniform; to the southeast (down the Muskingum River) it
increases by about 15 ft. per mi. and to the northwest

*See reference [24], Groups 54.1 – 54.3.
**See reference [17], Groups 48.1a – 48.3, reference [24],
Groups 59.3a – 59.4.
(upstream toward Zanesville) it decreases at the rate of about 30 ft. per mi.

Inspection of the Jonathan Mine with its low unit cost of operation confirms that the Maxville Limestone, which underlies the Pennsylvanian System in the McConnelsville area, might provide an excellent location for an installation.*

Sloping entrances could be driven through the Pennsylvanian System starting at the bottom of the Monongahela Formation and terminating in the Maxville Limestone. It is likely that about 2/3 of the length of these entrances would require continuous support of moderate strength, but no serious difficulties are foreseen.

The top of the Maxville Limestone is an old, undulating erosion surface, and without carrying out test drilling it is impossible to predict whether an adequate thickness of strong, competent limestone exists at any particular point below this surface. Moreover, should it be impossible to find sound limestone of sufficient thickness and extent, no particularly promising alternatives are currently known to exist above or below the Maxville bed.

13. THIN-BEDDED CELLULAR AND PLASTIC ROCKS, II

About 25 mi. south of Peoria, Illinois, near the northwest corner of Logan County, there is 400 ft. of till, composed primarily of glacial outwash clay and containing an occasional lens of sand

*See reference [24], Groups 59.1a – 59.2.
or gravel, which overlies some 300 ft. of Pennsylvanian coal measures [26][27]. The upper portion of these coal measures is composed of many thin layers of sandstone, shale, limestone, coal, and underclay. As in Ohio and West Virginia, the rocks in this region, with the exception of the limestone, are porous and may be expected to dampen out at least the high-frequency components of an approaching blast wave.

Below the Pennsylvanian coal measures are two clear and competent layers of limestone that appear to offer favorable sites for an underground center (Fig. 16). One starts at about 700 ft. and goes down to 850 ft., while the other begins at about 1100 ft. and goes down to about 1400 ft. If an installation were placed in the latter, it would have an additional 250 ft. of cover composed of limestone, sandstone, and shale.

It is not likely that entrances have been developed in this area; however, due to the low relief of the terrain, either inclines or vertical shafts would have to be excavated.

The information contained in this section is based on inferences drawn from three regions in central Illinois for which reports and logs of core drillings were available, namely two borings in Douglas County, one in Livingston County and one in Sangamon County. It is suggested that further study be undertaken before selecting a site in this area in order to avoid, for example, encountering those portions of the sand, gravel, and glacial till that may contain considerable amounts of water.
Fig. 16 — Representative geological column near the northwestern corner of Logan County, Illinois
14. CONCLUSIONS

This study indicates that although it may be advisable to construct large subterranean command and control centers in hard competent rock, such installations need not be covered by a great mass of similar or identical rock. Geological media such as glacial ice, diatomite, clay-shale, and broken uncompacted rock offer interesting possibilities as covering materials that may be more effective blast-wave attenuators than self-supporting rocks such as granite or limestone. Furthermore, many covering layers of dissimilar rock should have a damping effect on blast waves, especially in the high-frequency range. Finally, the presence of mined openings in the natural overburden, or the creation of new ones, may add significantly to the protective qualities of the covering material, particularly against the high-frequency components of a blast wave.

In view of the limited knowledge concerning the behavior of various combinations of rock when subjected to the enormous overpressures developed by the ground burst of a large nuclear weapon, it is suggested that theoretical and experimental investigations to check the validity of the deductions in this report may well repay the investment. Although it may be said that any natural cover is better than none, there are sound geological reasons for preferring certain types of natural overburden to others. There should be more research directed toward getting information on
(1) the advantages and disadvantages of various geological arrangements in site selection, (2) the attenuating effects of various combinations and thicknesses of rock and soil, and (3) the destructive effects of blast waves on an installation at a given depth in a specified geological environment.
REFERENCES


