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Ernest O. Lawrence Radiation Laboratory

PLOWSHARE

Livermore, California

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Edward Teller

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Introduction

Twenty years ago the first nuclear reactor was put into operation on the campus of the University of Chicago. Today nuclear reactors can produce usable energy at a real cost less than that paid for energy in 1942. In the meantime prices have gone up by a factor of 2 or more; the price of energy generation from conventional sources has dropped. Thus the real cost of energy is not more than one-third of what it was at the time when Fermi produced the first successful chain reaction. As a consequence nuclear energy is not yet competitive. It has contributed to the national economy by providing additional incentive for lower cost of the conventional installations.

In another field the atomic nucleus has made a great contribution to our economy. The use of isotopes for various industrial purposes has developed into a $ 100-million-per-year business. The impact of the isotopes is real but it is not concentrated in any one field and thus we are not acutely aware of these useful developments.

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*This paper is based on the annual lecture of the American Nuclear Society given on November 28, 1962. I am deeply indebted to Dr. Glenn Werth for his help in preparing the manuscript.

There is a third field which could and should develop within the next few years into a massive and remunerative application of nuclear energy. This is the use of nuclear explosions for peaceful purposes. Altogether, more conventional explosives have been used so far in peaceful industry than in wartime destruction. That nuclear explosives have not yet made their contribution in a constructive manner is due to two reasons. One is that nuclear explosives become economic only when used in rather large units — and large explosions must, of course, be handled with particular caution. The second reason is that nuclear explosives produce radioactivity, which is dangerous in the large quantities that occur in the immediate neighborhood of the explosion. Furthermore, the discussion about fallout has resulted in exaggerated and unwarranted fears so that even small quantities of radioactivity which are in themselves not harmful are viewed with alarm; this impedes actual progress of any peaceful enterprise.

Even during the war we discussed the possibility of using nuclear explosions for constructive purposes. Shortly after the war John A. Wheeler proposed the use of underwater nuclear explosions for the purpose of producing radioactive isotopes which could later be extracted from water collected on the explosion site. A little later Theodore B. Taylor made a more detailed proposal of nuclear explosions under ice or underground for similar purposes. But the first systematic consideration of the peaceful uses was started in 1957 by Harold Brown and Gerald W. Johnson at the Livermore Laboratory.*

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*H. Brown and G. W. Johnson, "Non-Military Uses of Nuclear Explosions," Lawrence Radiation Laboratory (Livermore) Rept. UCRL-5026 (June 1958). The effort is now carried on by a numerous group in Livermore under leadership of Roger Batzel and Gary Higgins.

This effort has been continued in Livermore with increasing vigor. For understandable reasons it has been named "Project Plowshare."

In the meantime the Russians have recognized the possibility of work in this area. At the time of the first Russian explosion in 1949 Vishinsky claimed that the Soviet effort was to serve constructive aims. The statement was:

> "Right now we are utilizing atomic energy for our economic needs in our own economic interest. We are raising mountains; we are irrigating deserts; we are cutting through the jungle and the tundra; we are spreading life, happiness, prosperity, and welfare in places wherein the human footsteps have not been seen for a thousand years."

There are indications that the Russians have followed up this early proposal. In 1956 explosions of many kilotons were used in China for the purpose of uncovering ore fields. In 1957 the Kolonga river in the Ural Mountains was deflected into a new bed by 30 explosions of 100 tons each which produced overlapping craters forming a new river bed. We have been most interested in these and similar experiments and we asked the Russians to show us the explosion sites and discuss with us these constructive possibilities. Unfortunately the Russians refused any such cooperation and did not permit inspection of the sites. They claim that the explosions were performed by conventional high explosives, a statement which we could not verify since we could not enter the sites. What we do know is that explosions similar to those performed by the Russians could have been performed with nuclear explosives, that such explosions even when performed by conventional explosives are needed as a preparation for bigger explosions in which nuclear power is utilized, and that for really big enterprises nuclear explosions are certainly more economical than the application of chemical high explosives. Thus the early words and the later deeds of the Russians lent some plausibility to the assumption that Russian nuclear power is indeed being used in this important field.

Unfortunately a discussion of Plowshare must remain incomplete in one respect. We cannot enter into a detailed discussion of the nuclear explosive itself. This is almost as bad as giving a performance of Hamlet in which the Prince does not appear. One important general statement, however, can be made: The best tool for Plowshare is the thermonuclear explosion.

The idea of the hydrogen bomb has been identified with an exceedingly large explosion. Indeed thermonuclear explosives lend themselves particularly well to big explosions and it was in this field that the hydrogen bomb became recognized as a tool of great military importance. However, with advancing knowledge we have learned to make less powerful thermonuclear explosives, and these are of great importance because they furnish relief from the two difficulties facing the acceptance and practicability of the Plowshare proposals. By using thermonuclear explosives we can avoid producing the large quantities of radioactive materials characteristic of fission explosions. Having produced a crater we might enter it at once after the explosion without exposing ourselves to more radioactivity than the personnel of our Laboratory are permitted to take as a routine matter. Explosives of such cleanliness have not yet been produced, but there is no doubt that they are feasible and require only a few more years for development.

A second and no less important advantage of thermonuclear explosions is their lower cost in comparison with fission explosions, for a given energy yield. With further development of the art, it is possible that nuclear explosives will become competitive with conventional explosives in sizes down to a thousand tons or in some cases even a hundred tons TNT equivalent. Thus the thermonuclear explosives which were once considered as an instrument of ultimate terror might become the means by which the first large-scale peaceful use of atomic energy will become practically feasible.

Earth-Moving Devices

The discussion of the peaceful applications of nuclear explosives has produced some concrete ideas that surely can be realized and it has also produced some promising possibilities which for the time being we must consider as dreams. First, we shall mention those applications about which we can feel quite sure. They boil down to a single fact: We can make a hole in the earth — if anybody wants to do that. As a matter of fact, there are some important reasons why one should want to move big quantities of earth.

A kiloton explosion placed 100 to 200 feet underground will produce a crater approximately 300 feet in diameter, which is the length of a football field. Bigger explosions will move (in first approximation) proportionally bigger amounts of dirt. Thus a megaton explosion will move a thousand times as much earth as a kiloton explosion, which means that each dimension of the hole that is produced will be greater by a factor of 10. Thus the crater from a megaton explosion placed 1000 to 2000 feet underground will be about 3000 feet in diameter.* Such a single hole scooped out from an appropriate shoreline can form a crude harbor.

A better harbor or even a canal can be obtained by setting off a number of simultaneous explosions. If the craters of these explosions over-

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*According to a more accurate law which takes into account the effects of gravitation, the linear dimension of the crater will increase with the 0.3 power of the yield rather than with the 1/3 power.

lap sufficiently one can form a canal with reasonably smooth sides. Thus harbors can be carved out in a way adapted to the nature of the terrain. A long row of such explosions could produce sea-level canals cutting across sizable bodies of land.

One obvious question is the expense of such an operation. According to statements of the Atomic Energy Commission a nuclear explosion can be performed at the approximate cost of $ 1 million. Kiloton explosions are somewhat less expensive while megaton explosions will cost a little more. In actual fact these two explosions (megaton vs kiloton), which will move masses of earth in the ratio of approximately a thousand to one, can be delivered at a cost ratio of only two to one.* From this it is obvious that in a bigger explosion we will pay considerably less for moving one cubic yard. The cost will be as little as 2 cents per cubic yard in the megaton explosion, while in the kiloton explosion we are faced with an expense of $10 per cubic yard. The conventional cost of excavation is about $1 per cubic yard. Thus, nuclear explosions would be more economic at the present time in case explosions of 50 kilotons or more are employed. In the future, smaller nuclear explosions will become economically usable.

The creation of a harbor or a canal of this type will make it necessary to evacuate people to a distance that may vary between 3 and 15 miles, according to the size of the explosion. In case appropriately clean nuclear explosives are developed it will be possible to return into the neighborhood of the explosion site immediately after the explosion has been performed. A reasonably but not completely clean explosion was tried in Nevada last

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*It is entirely possible that with progressing technologies and great demand these costs will be very substantially reduced.

summer. This explosion, called the Sedan shot, is shown in Fig. 1A, and the hole (1200 feet in diameter, 300 feet deep) in Fig. 1B. A sizable harbor can be blasted for an amount of money between $1 million and $10 million. This means that we can make a harbor for the kind of money we used to pay merely to equip a harbor.

The obvious difficulty in proceeding with this plan is that in places devoid of population no harbors are needed, while in polulated areas no explosions are tolerated. There will be, however, cases where the creation of the harbor itself will later attract the people. The possibility of forming pairs of harbors on the sides of channels of adjacent islands of the Hawaiian chain has been discussed. It is remarkable that in these islands originally populated by the most daring of navigators there is at present a minimal flow of sea traffic. The type of harbors we have mentioned could produce greatly increased traffic and commerce throughout most of the island chain, but unfortunately the Hawaiians are reluctant to be the first to try the experiment.

Another possibility would be a harbor on the Katalla River. The harbor is shown in Fig. 2, together with the position of extensive coal deposits. As seen in Fig. 3 (which shows all of Alaska), the harbor is situated in an ice-free region of the ocean. At the present time the nearest harbor facility is at the town of Cordova (see Fig. 2), which is separated from the coal fields by the broad and shallow Copper river as well as by a glacier or moraine across which transportation is impracticable.* The question whether the coal fields can be mined in an economic fashion even if a harbor were available is not completely decided, but should this project turn out to be feasible, the

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*A railroad in this region had been constructed but could not be maintained.

result may well be a drop in the coal prices throughout the Pacific area. It is interesting to note that Japan today imports its coal from Pennsylvania via the Panama Canal. If the harbor on the Katalla River should help Japanese industry, Japan might become the first country to share in the benefits of a peaceful explosion as it was the first to suffer from a nuclear bomb.

It is hardly possible to predict which of the harbor projects might become most important at the earliest time. It is, however, a well-known fact that extensive coast lines such as the western coast of Africa, South America and Australia are badly under-supplied with harbors.

We have already mentioned the possibility of making sea-level canals. Many examples will come to mind quite easily. Perhaps the most obvious and most exciting canal project is the proposal to make a new sea-level canal across the American Isthmus using nuclear explosives. Statistics over the past years indicate that the present canal will be inadequate within ten years. Even today many ships are too big and must go around South America. A sea-level canal could be constructed with nuclear explosives along several routes in either Panama, Columbia, or other countries of Central America for a cost no greater than will be required if the Panama Canal should be widened by conventional methods. Yet the latter possibility would give us a lock canal of marginal value. A sea-level canal would be much cheaper to operate and would solve the problem of traffic for good. It also would be virtually indestructible.

Two others which have not yet been discussed very extensively are a canal cut across the Aleutian chain and a canal constructed on the Kra Isthmus, the neck of the Malay Peninsula. The accompanying Figs. 3 and 4 show these canals. Fig. 3 also shows the location of a dam to be discussed below.

The difficulties of circumnavigating the Aleutian island chain has held the number of ships which visit western Alaska per year to approximately half a dozen. The canal on the Kra Isthmus will cut almost a thousand miles from the sea route between Japan and India, a project which would be most rewarding but would also be quite expensive. We estimate the cost of the Aleutian canal at $20 million, while the Malay canal will need almost a billion-dollar investment. But for that money a sea-level canal can be constructed while conventional methods will produce either a very much less satisfactory lock canal or a terribly expensive sea-level installation.

Apart from harbors and canals which are so important to navigation, nuclear explosions can contribute to regulating rivers and to the increase of water supply. The most outstanding example of such an enterprise is probably to be found in Australia. The eastern Pacific Coast of that continent is well watered, but beyond the coastal range precipitation becomes exceedingly sparse. Compared to the Australian desert, our arid Southwest is like the Garden of Eden. The Australians are already engaged in the herculean labor of deflecting rivers from the eastern slopes of their coastal range toward the west. In an enterprise of this kind nuclear explosives, by the help of closing canyons or opening new outlets, will become most economic tools.

The first and simplest application of nuclear explosives in the Australian desert might be the use of big craters as catchment basins for water in the western desert itself. Like in the arid regions of the United States, torrential rainfalls occur occasionally in the Australian desert.*

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*As I write this (January 1963) I read with satisfaction that the decennial downpour in West Australia has just recurred. Having wrongly ascribed our hard winter to nuclear testing, the news media have rightly refrained from using the same explanation for the Australian cloudburst. It seems to be axiomatic in public discussions that nuclear explosions can have only ill effects.

The resulting flood waters, however, are only partially contained. A major fraction is wasted. Appropriate catchment basins could provide an early and cheap supply.

The distribution of water is becoming more and more important in the United States also. The most ambitious plan of conducting the water of the Feather River into the central valley and to the neighborhood of Los Angeles and San Diego is most impressive, both because of its cost and its beneficial effects. There is some preliminary consideration being given to the question of whether or not portions of this project could be more cheaply executed with the help of Plowshare. If this enterprise is to be carried out, clean and cheap nuclear explosives will be most urgently needed.

Water regulation of still another type can be illustrated in connection with the Rampart project in Alaska. The Yukon River flowing west from Canada into Alaska breaks through a mountain range in a canyon by the name of Rampart, northwest of Fairbanks. It would be easily possible to close this canyon with the help of nuclear explosions and to divert the Yukon River to its somewhat older tertiary bed, which is parallel and a little south of the present course of the river. On an appropriate place in this new bed one can erect hydroelectric installations before the river is deflected. The lake which will form behind the dam would stretch all the way back to the Canadian border and would cover a territory of wet permafrost in which no cultivation is possible, no buildings can be erected, and over which a vehicle cannot pass more than once without getting mired. If this practically uninhabitable region is covered with water, some improvement of the climate can be expected. But it is more important that the dam would provide twice as much hydroelectric power as the Coulee Dam. At present Alaska is of course not capable of absorbing so much power. But the formation of the lake would take ten years and if we add to this period the time which is undoubtedly going to pass before a decision on the Rampart Project is made, the development of Alaska which will have occurred in the meantime will make these great amounts of electrical power really useful. The location of the proposed dam is shown in Fig. 3.

Navigation, hydroelectric power, and irrigation by surface streams and reservoirs still do not completely exhaust the possible uses of nuclear explosives in water regulation. It is possible to break up impermeable layers with the help of nuclear explosives. In the first underground nuclear shot in 1957, which was called the Rainier shot, a 1.7 kiloton explosion shattered approximately 200,000 tons of rock and made this material at least temporarily water permeable. The amount of rock shattered and the time during which the material will remain in the water-permeable condition depends of course on the nature of the rock. But it is clear that under some conditions very great holes can be punched into geologic formations which prevent water from seeping into an aquifer. That underground water can supply flourishing agriculture has been amply demonstrated in Phoenix and Tucson. In the long run, however, these underground water deposits will have to be replenished. Nuclear explosives might turn out to be the proper tools with which the seepage and flow of underground water can be regulated. Before this can happen it will be necessary to make a most thorough study of underground hydrology.

This last topic cannot be strictly called an earth-moving project. There are still other applications in which it will be highly profitable to move great quantities of earth. The most important of these is to remove overburden from extensive underground mineral deposits. The mining of iron and coal is economically possible only if the deposits are reasonably close to the surface. With the help of nuclear explosions it will be possible to remove layers as thick as 1000 feet and our wealth of mineral deposits throughout the world can be most significantly increased. This factor alone could become decisive in the spread of industrialization throughout the world. It has been claimed that scarcity of raw materials has furnished an important reason, perhaps the main reason, for wars in the modern world. While this claim may well be exaggerated, a greater abundance of essential raw materials might indeed be the condition which in the long run is best suited for peaceful cooperation throughout the world.

Dreams

A really novel field like that of nuclear explosions is apt to open completely new avenues of approach. There is in fact no scarcity of ideas. Whether these ideas are feasible or not remains to be seen. Some of them are apt to work out. Others will fall by the wayside. The very discussion of this topic will generate additional ideas which may well be more fruitful than those proposed so far.

One suggestion that appears plausible is to use nuclear explosions underground in order to deposit heat and later to mine this heat by circulating a heat-exchange fluid and using the hot vapor produced underground to drive turbines on the surface. A very small-scale attempt to explore this possibility was performed in the Gnome explosion on December 10, 1961. A 3-kiloton explosion was set off 1200 feet underground in a salt deposit near Carlsbad, New Mexico. The explosion produced a cavity of a million cubic feet (Fig. 5). The surface above the explosion rose several feet and then fell back to a position a little less than two feet above the original level of the ground. Thus an extensive flat dome was formed over the explosion site and the volume of this dome corresponds to the free volume of the underground cavity.*

Because of insufficient knowledge of how to stem the gases in a nuclear explosion, a gaseous discharge was emitted from the Gnome explosion via a 1000-foot underground tunnel and a 1200-foot vertical shaft as shown in Fig. 6. The discharge consisted mostly of water vapor. Approximately 150 tons of water was boiled out of the salt and associated rock containing 1 or 2 percent fossil water. This vapor also carried along most of the gaseous radioactive products. Since the location and the meterological conditions had been chosen with the possibility of just such a discharge, the released radioactivity did not produce any damage. In fact, it was soon sufficiently dispersed as to fall below the level at which observation is possible. Due to these developments, however, we have gained the important knowledge that gaseous radioactivities produced in nuclear explosions underground can be readily and almost quantitatively recovered. Production of such radioactive materials might at some time become of economic importance.

But as to one of the original purposes of the Gnome explosion — to study the feasibility of recovering heat deposited by the nuclear explosion in salt — the answer we can now give is that it is not feasible. There is little doubt that in a repeated explosion the water vapor could become confined underground. However, when we dug into the Gnome cavity and made observations it was found that the water vapor entrained some of the salt. Due to the corrosive nature of this vapor, grave practical problems arise. It might be possible at some future time to deposit, by megaton explosions, enough heat

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*Rawson, D. E., C. R. Boardman, N. Jaffe. The environment created by a nuclear detonation in salt, Project Gnome Report No. PNE-107F, Lawrence Radiation Laboratory, Livermore, California (to be published).

underground so as to drive a big hydroelectric plant for a month. It is even possible to show that the expense of the nuclear explosives is small enough to make such an operation attractive. However, in a steady operation the nuclear explosions would have to be repeated approximately once a month. The cost of maintaining the equipment under such conditions makes this possibility look most unattractive.

A variant of this plan, however, may turn out to be most hopeful.* One may explode a nuclear charge of a megaton or more 2 or 3 miles underground in a region which for reasons of geological history happens to be at a high temperature. The nuclear explosion will not be used for producing heat but only for cracking the rock which already contains much greater amounts of heat energy. Thus a single 10-megaton nuclear explosion might make accessible a heat reservoir corresponding to 100 megatons. One attractive use of this possibility may be the distillation of sea water. At a depth of 2 or 3 miles the pressure exerted by a water column would be greater than the critical pressure of water. As a consequence, distillation can be carried out in a thermodynamically favorable manner without recourse to the usual expensive multi-effect distillation. Some plans have been considered in which sea water would be poured down into this broken underground region produced by the explosion. It is hoped that the porosity and permeability in the rubble resulting from the collapse of the cavity formed by the explosion would be sufficient to contain the salt left behind in the distillation process. If these hopes turn out to correspond to reality, sweet water could be obtained at a cost between $5 and $50 per acre foot. While in my opinion this is not very

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*The following ingenious possibility was suggested by Professor George Kennedy of U. C. L. A.

likely, the rewards of a successful operation of this kind would be exceedingly great.

In the meantime we have followed the initiative of Dr. George Kennedy* and practiced the art of drilling into hot substances by exploring the lava lake formed during the eruption in 1959 in the crater of Kilauea Iki. We have succeeded in drilling a 1-7/8-inch hole through the solid lava surface and found liquid lava at a depth of 21 feet. The solid lava floats on the underlying liquid due to the buoyancy provided by the bubbles contained in the solid. The experiment gave us the first really reliable measurement of the temperature of liquid lava in its natural state, which was found to be about 1075°C. We also were able to analyze the gases released from the lava, which turned out to be to a great extent water vapor with small quantities of argon, carbon dioxide, sulfur dioxide, and hydrogen.

Another and potentially more powerful application of nuclear explosions is connected with a strange variety of mining. It has been emphasized, particularly by Dr. John Grebe, that in deep underground nuclear explosions the earth can be considered as a retort, the nuclear power as the heat source, and that we may in this way execute chemical reactions on a very big scale. As a result we may change the minerals before we extract them from the earth and make them available in a much more useful form.**

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*George Kennedy and Gary Higgins, Water and Power from Earth Heat, Part I, Institute of Geophysics and Planetary Physics, Univ. of California, Los Angeles 24, Calif. Feb. 1, 1962. D. E. Rawson and W. P. Bennett, Results and Power Generation Implications from Drilling into the Kilauea Iki Lava Lake, Hawaii. United Nations Conference on New Sources of Energy, E/CONF/35/G/5 April 1961.

**John J. Grebe and E. V. Luoma, Dow Chemical Co., Large Scale Chemical Reactions Underground; Proceedings of the Second Plowshare Symposium, May 13-15, 1959. Part IV, UCRL-5678.

There are abundant possibilities for such experimentation, but most of them do not appear to be economical. We have found that in nuclear explosions some hydrogen is produced. But no estimate has yet shown that the price of this hydrogen could be made sufficiently low. If a nuclear explosion takes place in limestone, great amounts of carbon dioxide will be liberated. But the price of the carbon dioxide is so low that again no economic advantage can be gained. One specific suggestion of Dr. Grebe is to explode the nuclear device in limestone carrying oil shale. In this combination it is likely that some calcium carbide will be formed. Of course, the formation of calcium carbide needs exceedingly high temperatures, but if the material is appropriately loosened up before the explosion takes place the change in volume under high pressure will produce the high temperatures needed in a rather extensive manner. Once calcium carbide is formed one can let this react with water and produce acetylene, which in turn can be used in a host of most important chemical reactions. The main difficulty with this proposal is that the acetylene is quite likely either to polymerize or explode before it can be brought to the surface or before it can be made otherwise to react profitably with appropriate materials.

Another possibility that might be more feasible is to perform the explosion in an iron silicate which carries oil shale. Under these conditions the hydrocarbon will reduce the iron silicate into metallic iron at temperatures in the neighborhood of 800°C. In this way we may produce iron granules which could be brought to the surface and separated from the rest of the substances by either gravity or magnetic action. Thus, iron deposits could be exploited which are otherwise not usable. In addition, one would save the transportation of the useless silicon and oxygen and one actually would start at the mine head at a more advanced stage of the metallurgical process.

Perhaps the most hopeful of these chemical applications is the use of nuclear explosives in deposits of oil shale or tar sands. Near the Athabasca River in Alberta there are tar-sands deposits equal to the wealth of all the oil of Arabia. Similar or greater quantities of oil are available from shale near the Colorado-Utah-Wyoming boundaries in the Green River region. In the case of the tar sands, heating of the material by the nuclear explosion itself should suffice to transform the material into a liquid state that can be pumped to the surface.* In the case of the oil shale, much greater heat is needed and the main purpose of the nuclear explosion would be to shatter the material. The explosion would then have to be followed up by pumping air into the shattered region and to drive out the kerogen, i.e., the hydrocarbon contained in the rock, by burning a portion of the shale.** Similar fire-drive procedures have been successful in obtaining hydrocarbons from viscous oil deposits.***

The strange possibility of using the nuclear car to move the fossil horse is in the long run a promising one. At the present moment interest in this particular field is not high due to the present oversupply of oil. It would be easiest to exploit the Alberta tar sands, but due to the high sulfur content of these deposits and their remote location the economic usefulness of that particular project seems to lie in the indefinite future.

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*M. L. Natland, Project OILSAND; presented to the Joint Technical Feasibility Committee; Ottawa, Ontario, Canada; July, 1959 — Richfield Oil Co.

**Application of Nuclear Explosions to Oil-Shale Utilization, Bureau of Mines; Laramie Petroleum Research Center, MISC-1959-150, Jan. 1959.

***In-Situ Combustion, McNeil & Moss, Oil & Gas Journal, 15 Sept. 1958.

Scientific Uses of Plowshare

It would be very strange if the remarkable event of a nuclear explosion did not produce results of direct scientific interest. Actually, such results have already been produced in a more or less incidental manner. Our plans on Plowshare include as a most important point the full scientific exploitation of nuclear detonations.

The energy released in nuclear explosions is of the same order as energies released in earthquakes. This fact has considerable importance for seismology. Comparison of signals from nuclear explosions with signals from earthquakes has made it possible to obtain a realistic value for the energies released in earthquakes.*

Another characteristic of nuclear explosions is that the time and location of the event is exactly defined, while the time and location of an earthquake is diffuse. As a result, times of travel of earthquake waves can be much more accurately determined from nuclear explosions than from natural events. Furthermore, nuclear explosions can be detonated near positions at which no natural earthquakes occur and in this way new paths of elastic waves can be explored.

An interesting example is the Gnome event of 1961. It has been observed that on a circle of a thousand miles drawn around the position of the event the intensities of the first waves differed by as much as a factor of 150.** Much higher intensities were observed toward the east than toward the west. The time of arrival was likewise unexpected in that a few percent higher velocities

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*Romney, Carl, J. Geophys. Research. October 1959.

**Romney, Carl et al., Travel Times and Amplitudes of Principal Body Phases Recorded from Gnome. Ball. Seis. Soc. Am. 52, p. 1057.

were measured in the waves traveling toward the east. The explanation of all this is that near the Mohorovicic discontinuity (which lies about 20 miles under the surface) standard variations of sound velocity occur; these variations appear to be different in the Mississippi basin. The fact that this basin is aseismic, together with the imperfection of usual seismic observations, had hidden this particular property of the Mississippi basin from our seismologists up to the time of the Gnome event.

Another example of the same kind is the exploration of the earth layers under Antarctica. It is generally assumed that Antarctica is a continent. In reality we do not know whether this is so or whether the area of the South Pole is occupied by a frozen archipelago. In the first case the Mohorovicic discontinuity should be at a much greater depth than in the second. Since there are no earthquakes in that region, we are ignorant of the position of the discontinuity. Thus a single nuclear explosion under favorable conditions of observation could settle an important question in geophysics.

Nuclear explosives have been utilized for finding out more about the important neutron resonances in various elements. In 1958 George Cowan used time-of-flight experiments of neutrons emitted by a nuclear device to settle an important question in the theory of neutron resonances in uranium-235. Due to the abundance of these neutrons, it is possible to find the distribution of fission fragments produced by individual resonances. Cowan found some evidence for two types of resonances which might well correspond to compound nuclear states with spin values 3 and 4 as is expected from the one-half spin of the neutron being added and subtracted from the seven-halves spin of uranium-235.

In connection with the Gnome shot neutrons were moderated to energies between 10 and 100 volts. Dr. Cowan repeated his experiment and additional observations were carried out by a crew from Livermore.* One of the irradiated elements was hafnium. A resonance at 72.7 eV had been ascribed earlier to the neutron capture in hafnium-180. This assignment was confirmed. Actually, throughout the whole spectrum of hafnium a number of resonances which had not yet been assigned to a definite isotope have now been identified by the decay time of the activity which had been generated.

It is worthwhile at this point to consider in slightly greater detail the conventional and the Plowshare means of investigating neutron spectra. In both cases neutron velocities are determined by time-of-flight. In the usual experimental procedure, however, many very weak neutron pulses are produced, whereas in the case of the nuclear explosion a neutron pulse is available which corresponds to the neutron output of our best velocity selector instruments of a thousand years.** In the older experiments the total cross section of the bombarded material was the only thing that could be found by measuring the diminution of the beam intensity as it penetrated the material under investigation. In the Plowshare experiment the great intensity permits us to find and identify the isotopes which are created by the capture of neutrons of definite velocities. This procedure obviously permits a much more thorough analysis and similar principles can be applied even more generally to other phenomena occurring in nuclei.

An improved resonance analysis would be particularly important in the region of neutron energies between 1 and 400 kilovolts. These are the relevant

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*John A. Miskel, Manfred Lindner, Kenneth D. Marshall, Richard J. Nagle, Jr.

**This has been pointed out with great emphasis by Don Hughes of Brookhaven National Laboratory. His untimely death prevented his participation in the Gnome experiment.

neutron energies for reactors containing small amounts of moderators. The old method of velocity selectors are not very effective in this region and other methods, for instance the one using the neutrons from light nuclear reactions, are not applied easily in this energy region. The Plowshare method could fully explore this region and thereby make a great contribution to nuclear reactor technology, in particular, to the development of fast breeders.

Other experiments on nuclear physics could be carried out in a unique fashion with the help of nuclear explosions. Thus one could study the collision of pairs of neutrons. There are several ways in which this could be done. One of the simplest is to study the high-energy end of the neutron spectrum in a thermonuclear explosion.* The highest energy neutrons generated in such an explosion carry 14 million volts. Collision of two such neutrons, however, can produce even faster neutrons up to 28 million volts. The intensity of these very fast neutrons will permit a direct, though somewhat inaccurate, determination of the neutron-neutron cross section. More elaborate experiments will be needed to obtain the accurate cross section.

Nuclear physics may be even more rapidly advanced by another application of thermonuclear explosions. The first of these big-scale events (performed in 1952 under the code name of Mike) gave rise to a considerable number of successive neutron captures.** A maximum of eighteen neutrons

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*This was suggested by Dr. Stanislaus Ulam in the early fifties.

**A. Ghiorso, S. G. Thompson, G. H. Higgins, G. T. Seaborg, M. H. Studier, P. R. Fields, S. M. Fried, H. Diamond, S. F. Meek, G. L. Pyle, J. R. Huizenger, A. Hirsh, W. M. Manning, C. I. Browne, H. L. Smith, and R. W. Spence. Phys. Rev. <u>99</u>, 1048 (1955).

had been added to uranium-238. As a result, two new elements, 99 and 100 subsequently named einsteinium and fermium, had been isolated from the products which were generated by successive beta decays in the Mike debris.

With the progress of thermonuclear technology we now can produce the same type of explosions in miniature. In fact, a recent underground shot performed at the Nevada test site has given rise to a distribution of heavy elements very similar to those produced in the enormous Mike event. We are planning a shot by the code name of Coach which will be specifically designed to produce a maximum neutron flux giving rise to the greatest possible number of captured neutrons and to the heaviest and most strongly charged daughter nuclei. We expect that this procedure will make it possible to produce elements beyond lawrencium, which is element 103 and the last of the actinide series. Of course, transplutonic elements produced so far differ from each other only in the number of electrons present in the 5f shell. Their chemical properties are almost as similar as those of the rare earth series. Starting with element 104 we must expect completely new chemical properties, and thus the transplutonium chemistry will become more complex and more interesting.

Plowshare will make its great contributions not only in the structure of the nucleus but also in exploring how the outer electronic shell behaves under pressure. We have learned from experiments carried out with the help of high explosives up to two million atmospheres a great deal concerning the equation of state of matter.[*] The Russians have published results up to ten million atmospheres.[**] At these pressures remarkable changes occur in common materials. Iodine becomes an electronic conductor. Carbon can be compressed into a state of considerably higher density than diamond in which a carbon atom has presumably 8 or 12 neighbors rather than just 4. We have attempted to use Plowshare for high-pressure experiments, but found that more planning and instrumentation will be needed before this field can come to full fruition. In the end it is likely that Plowshare will yield much higher pressures and much more extensive results than could be obtained by using chemical energies.

Scientific experimentation in space using Plowshare has the quality of a dream within a dream. One obvious use of a nuclear explosion in space would be to measure the lifetime of neutrons.[***] At present this lifetime has been measured to an accuracy of a few percent. There can be no doubt that with the help of nuclear explosions and of detectors placed at various distances

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[*] R. G. McQueen, S. P. Marsh, Journal of Applied Physics, Vol. 31, pp 1253, 1269, 1960, Equation of State for Nineteen Metallic Elements from Shock Wave Measurements to Two Megatons. B. Alder, R. H. Christian, Behavior of Strongly Shocked Carbon, Phys. Rev. Letters, Vol. 7, p 367, 1961.

[**] S. B. Kormer, A. I. Funtikov, V. D. Urlin, A. N. Kolesnikova, Dynamic Compression of Porous Metal and the Equation of State with Variable Specific Heat at High Temperatures., Soviet Physics, JETP Vol 15, p 447, 1962.

[***] F. J. Dyson, Proposal for an Experiment to Measure the Lifetime of the Neutron, GA, D-957, General Atomics Div. of General Dynamics Corp., San Diego, Aug. 25, 1959.

between 100 and 10,000 kilometers from the explosion an accuracy of at least one-tenth of one percent can be attained.

Another simple experiment could compare light velocities at various frequencies. Of course, according to relativity there should be no frequency-dependence whatsoever. This fact has been verified by observing supernova explosions in neighboring galaxies. The signals in the various colors appear to arrive simultaneously in agreement with the prediction of relativity. A nuclear explosion would be much closer and much more sharply defined in time and would result in a comparison of the velocities of similar accuracy as obtainable from the supernova. But while the light from the supernova as observed from the earth covers frequencies of no more than a factor of 2, a nuclear explosion would permit observations reaching from the gamma-ray region to beyond the infrared. As one proceeds farther into radar and radio frequencies the actual propagation velocity will be influenced by the few free electrons which are found in interplanetary space. Thus the precise measurement of radio propagation can be used as a measurement of obtaining electron densities along the path.

While there can be almost no doubt about the outcome of the simple light velocity experiment, a further modification of this experiment might be valuable in connection with the theory of gravitation. General relativity predicts the same propagation velocity independent of the frequency even in case the propagation occurs in a strong gravitational field. However, the experimental basis of the beautiful theory of general relativity is less broadly based than Einstein's special relativity. Therefore, observation on a nuclear explosion carried out in the neighborhood of the sun would have the interest of supplying a direct confirmation of one of the basic postulates on which Einstein's theory of curved space is resting.

Electromagnetic fields produced by nuclear explosions are of considerable interest. In the initial phases of a nuclear explosion in space, the gamma rays emitted by the explosion will release Compton electrons from the surface of the explosive. This will result in a positive charge on the explosive and an electrical potential of a few million volts will develop. Beyond that point the Compton electrons will fall back upon the nuclear explosive and no further charge will occur. It is possible, however, to place near the nuclear explosive a great quantity of thin foil of an appropriate material. Under these conditions Compton electrons will be ejected from each foil and charge differences can occur between any of the foils and the neighboring foil that happens to lie at a somewhat greater radial distance. In this manner potentials of hundreds of millions of volts or even thousands of millions of volts might be produced in the initial phases of a nuclear explosion. While this potential will last for only a very short time, nevertheless particles might be accelerated to very high energies and these particles could be used in interesting experiments.

If the thin foil is placed on one side of the explosive, then extended and strong asymmetric fields can be produced near nuclear explosions in space. Actually there are other methods by which the same result can be obtained. In any case the production of such fields will result in the emission of strong radar waves. And these waves in turn might be used in astronomical explorations.* Long- and short-wave radar waves of this kind being reflected from a planet such as Venus could give us most interesting information about the nature of the surface of that planet.

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*Thomas Gold, "Some Experiments with Explosions in Space," LAMS-2443, pp 31-41.

One characteristic property of the space age is that scientific exploration has become closely linked with undertakings requiring tremendous expenditures. An expedition to the moon will indeed be very costly and at the same time is likely to yield great scientific benefits in finding out the nature of our satellite as well as obtaining information, with the help of a lunar observatory, about electromagnetic waves emitted in all wavelengths by astronomical objects. Plowshare offers a possibility of decreasing the cost of such an expedition by providing the scientific explorers with one of the most important substances: water. It is likely that bound water exists in the rocks of the moon just as it is found in many of the minerals of the earth. Actually our oceans have been formed from the water vapor contained in volcanic eruptions. Ultimately one may say that the oceans have been boiled out of the rocks of our planet. Water must have been released when the craters of the moon were formed. But this did not lead to any permanent water cover since the lower gravitation of the moon is not sufficient to prevent the escape of the water vapor from our satellite.

It may be possible to duplicate our Gnome experiment on the moon. Just as the Gnome explosion has produced a great amount of water, so an underground explosion on the moon might result in the release of a hundred tons of this commodity. If we wanted to transport this amount of water in our rockets the price we would have to pay for it would be in the neighborhood of the value of 100 tons of gold.

The easiest step in the execution of any such project is to give it a name. In this case it would seem reasonable to call the procedure by which a violent blow will produce water from the lunar desert, "Project Moses."

The purpose of this lecture was to give you an impression of the main characteristic feature of Plowshare: its exceedingly wide applicability throughout fields of economic or scientific interest. If one wants to find the right applications, knowledge of the nuclear tool is not enough. One needs to have a thorough familiarity with the materials, with the processes, with all of science, with all the economics on our globe and maybe beyond. Our group in Livermore is insufficient to meet such a challenge in an adequate way. Only the most widespread participation of scientific and technical talent is likely to exploit Plowshare in a manner commensurate with the great promise and the great variety of this new and exciting enterprise.

Work performed under the auspices of the U. S. Atomic Energy Commission.

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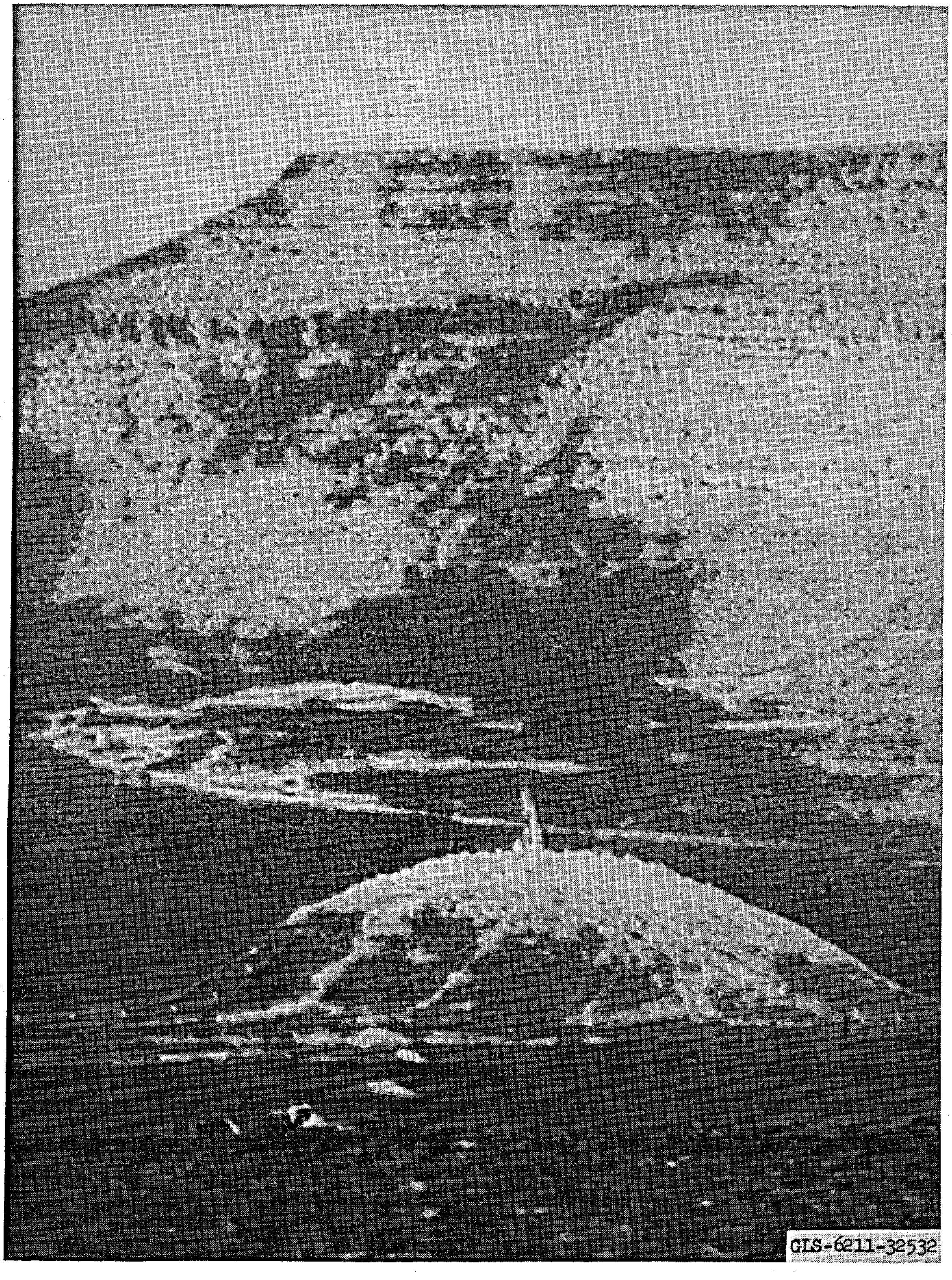

Fig. 1A. Sedan shot.

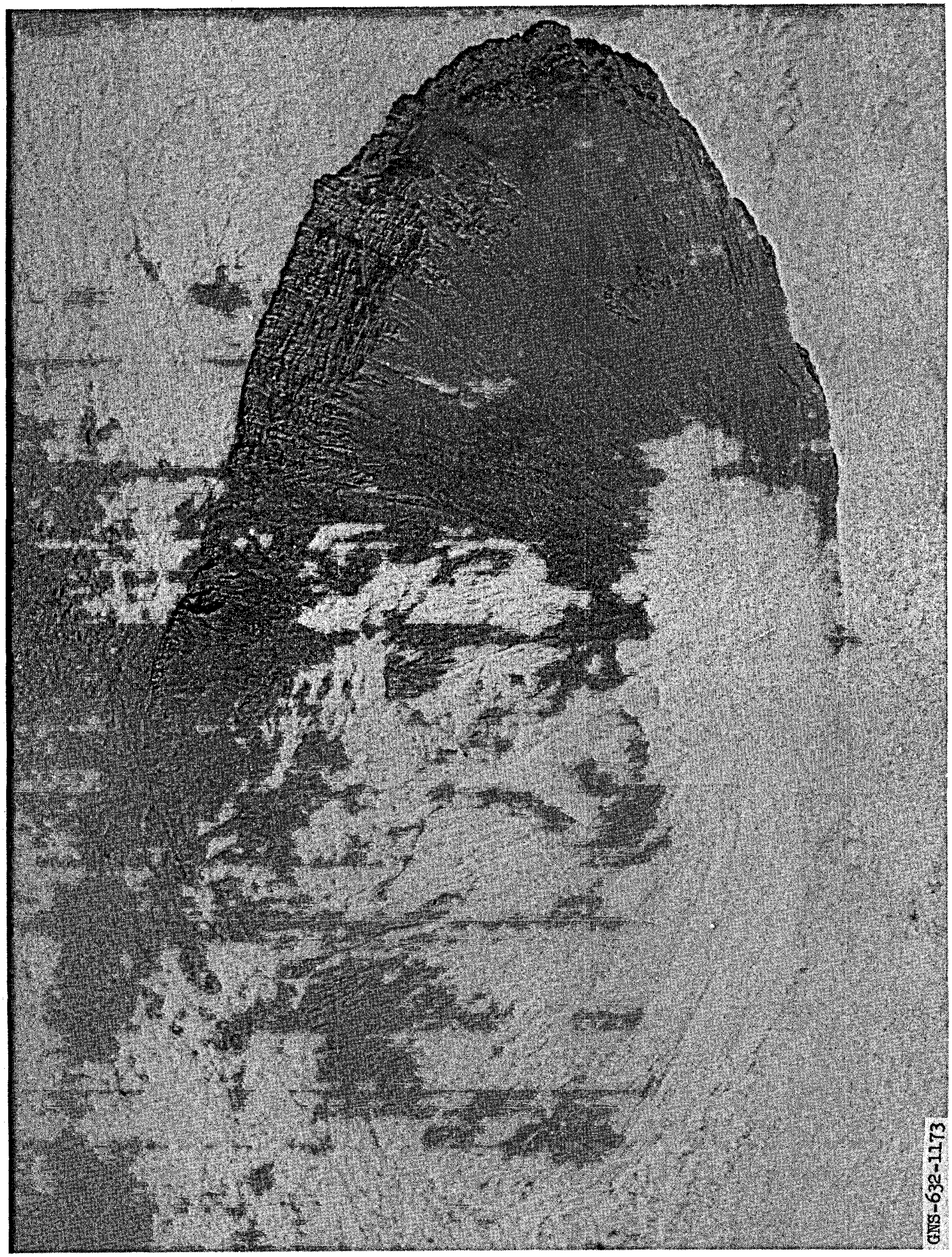

Fig. 1B. Sedan crater.

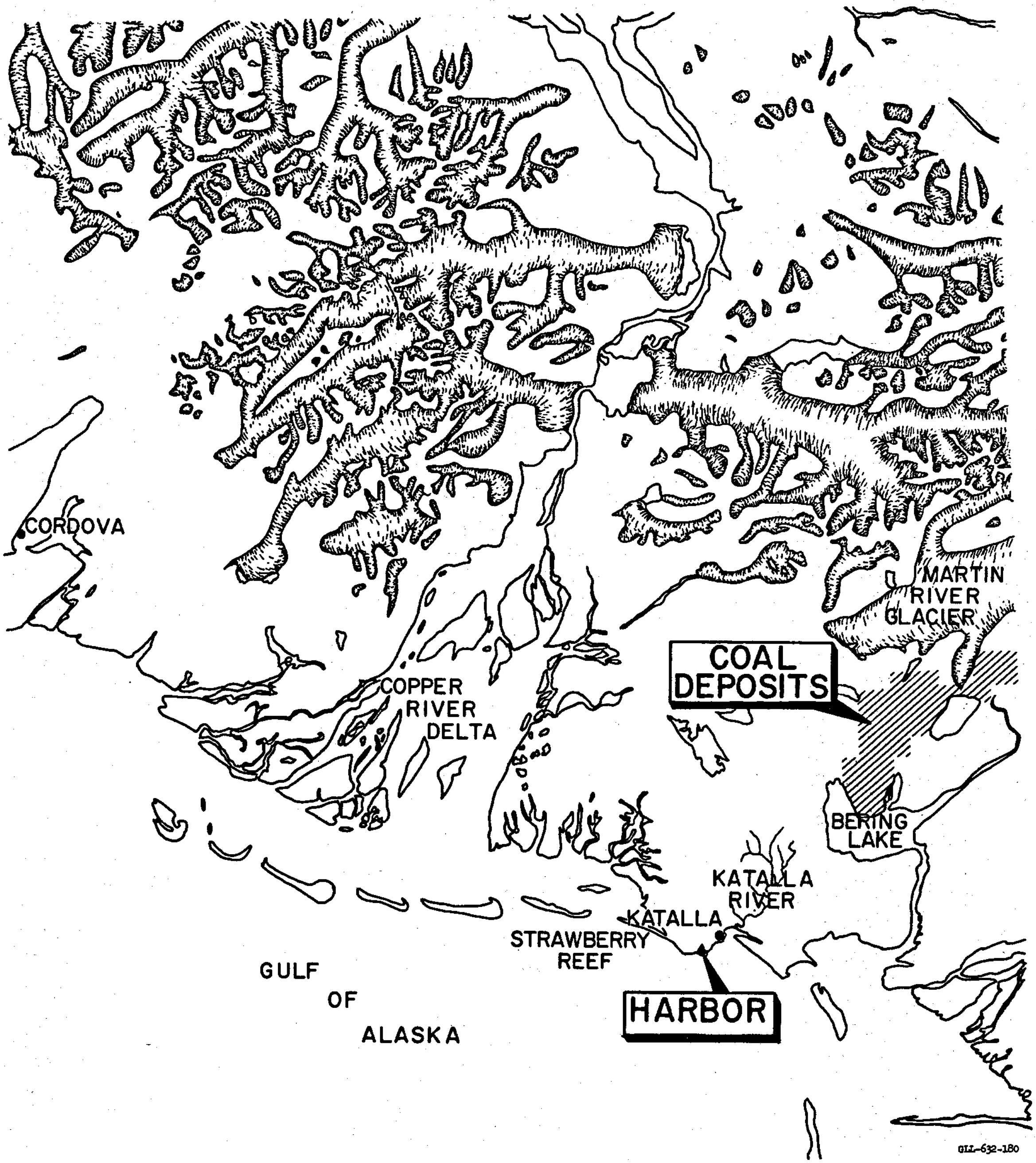

Fig. 2. Possible harbor site at the mouth of the Katalla River in Alaska.

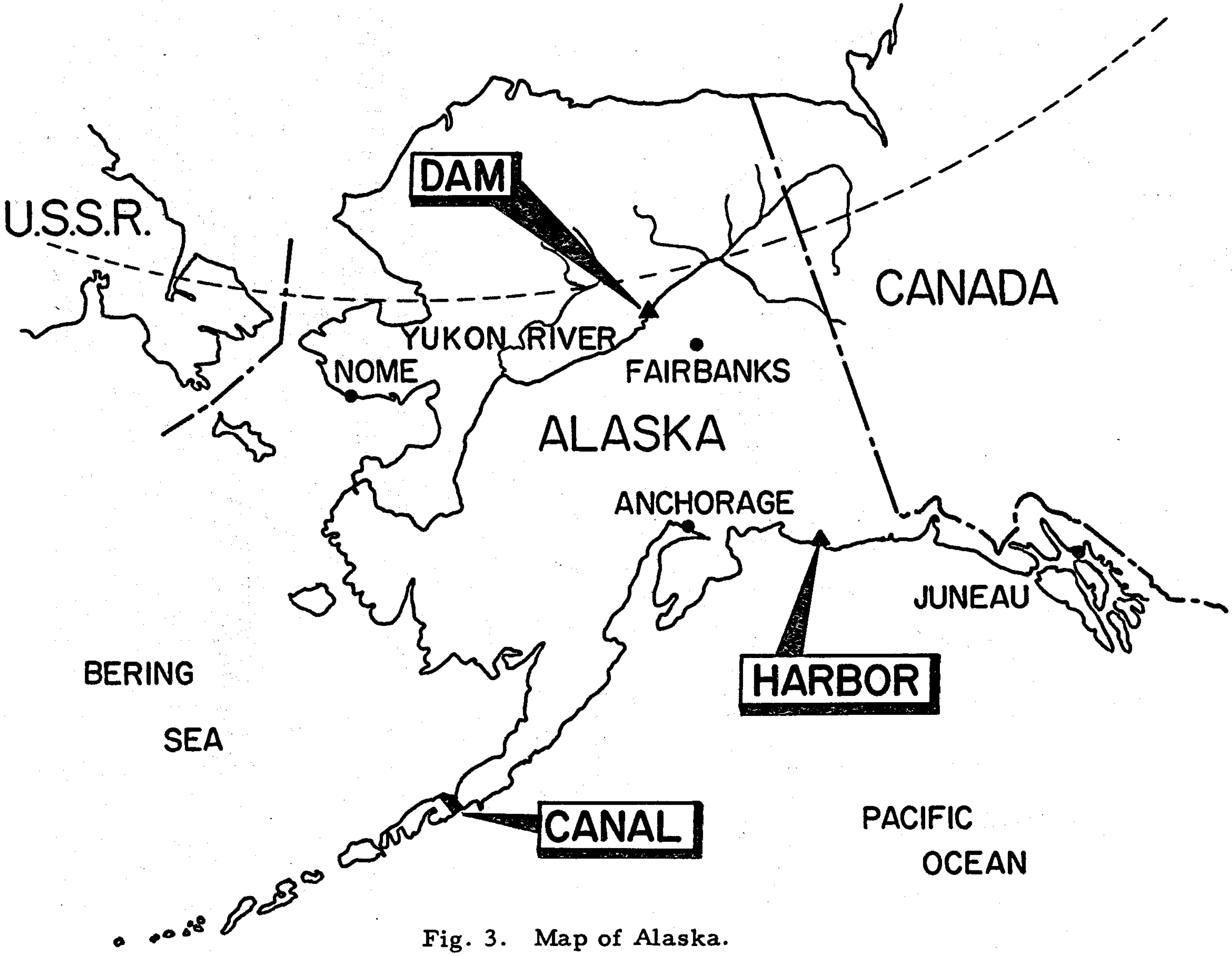

Fig. 3. Map of Alaska.

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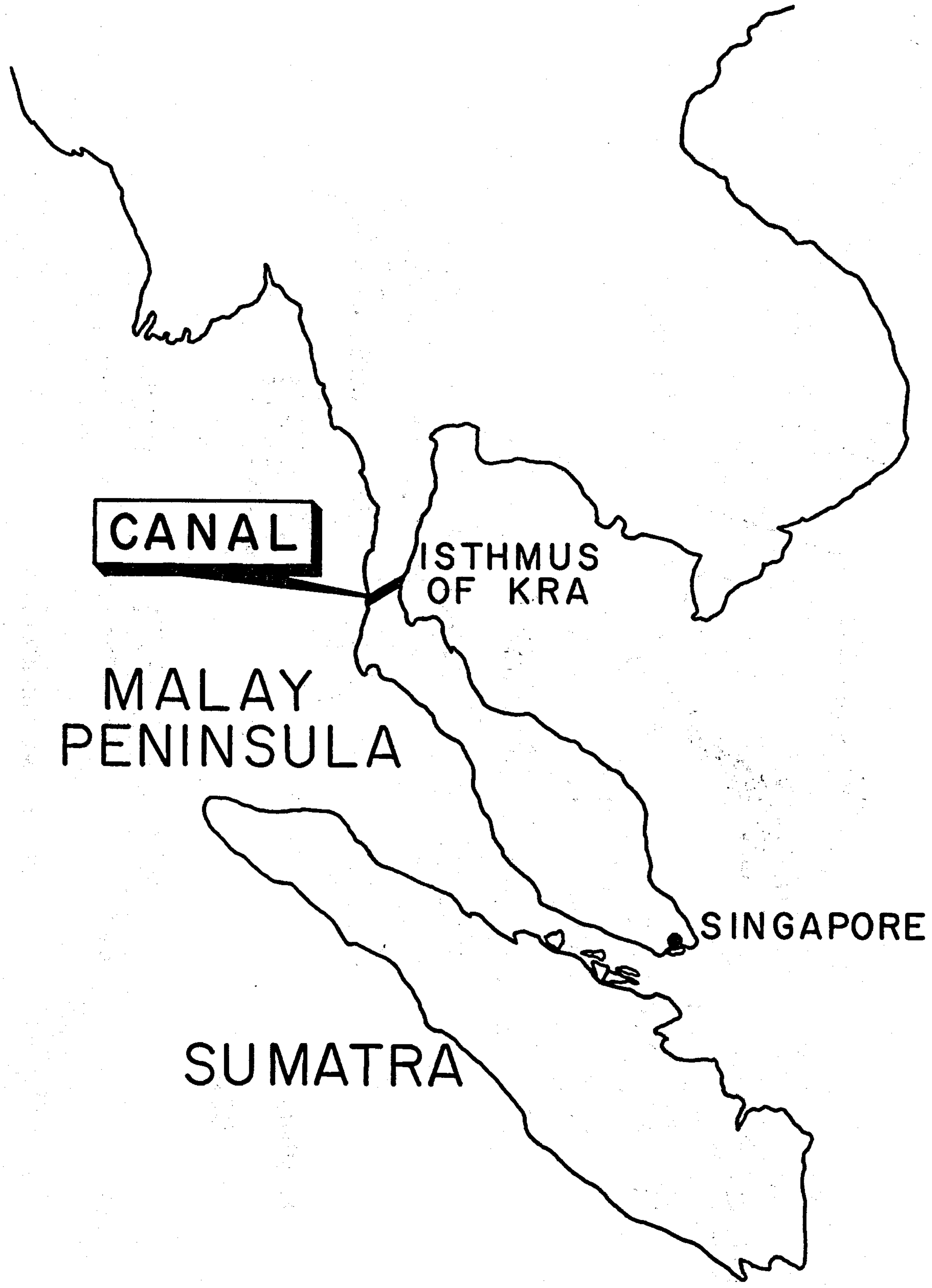

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Fig. 4. Map of the Malay Peninsula showing the possible site of a canal across the Kra Isthmus.

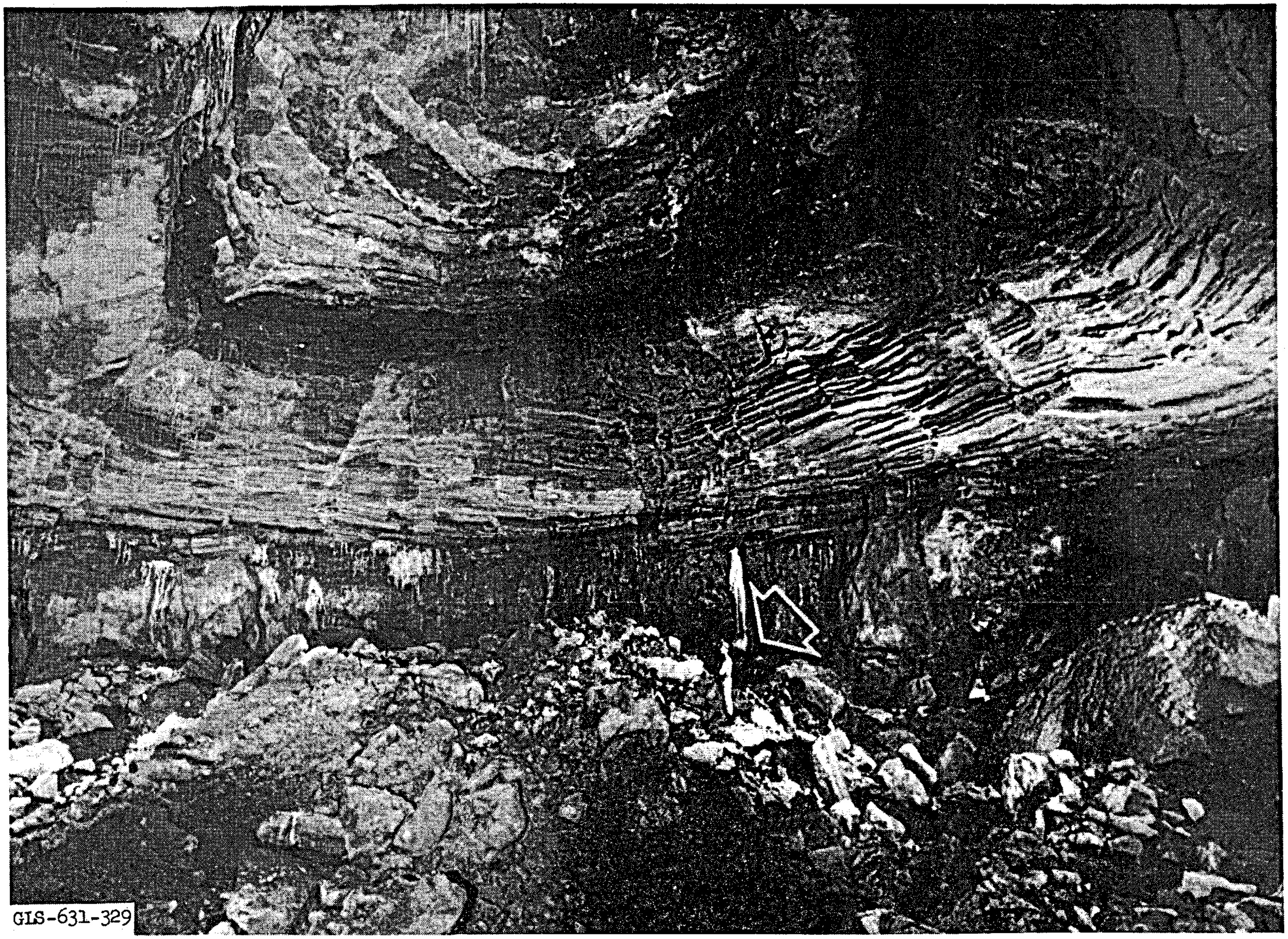

Fig. 5. Cavity produced by the Gnome explosion.

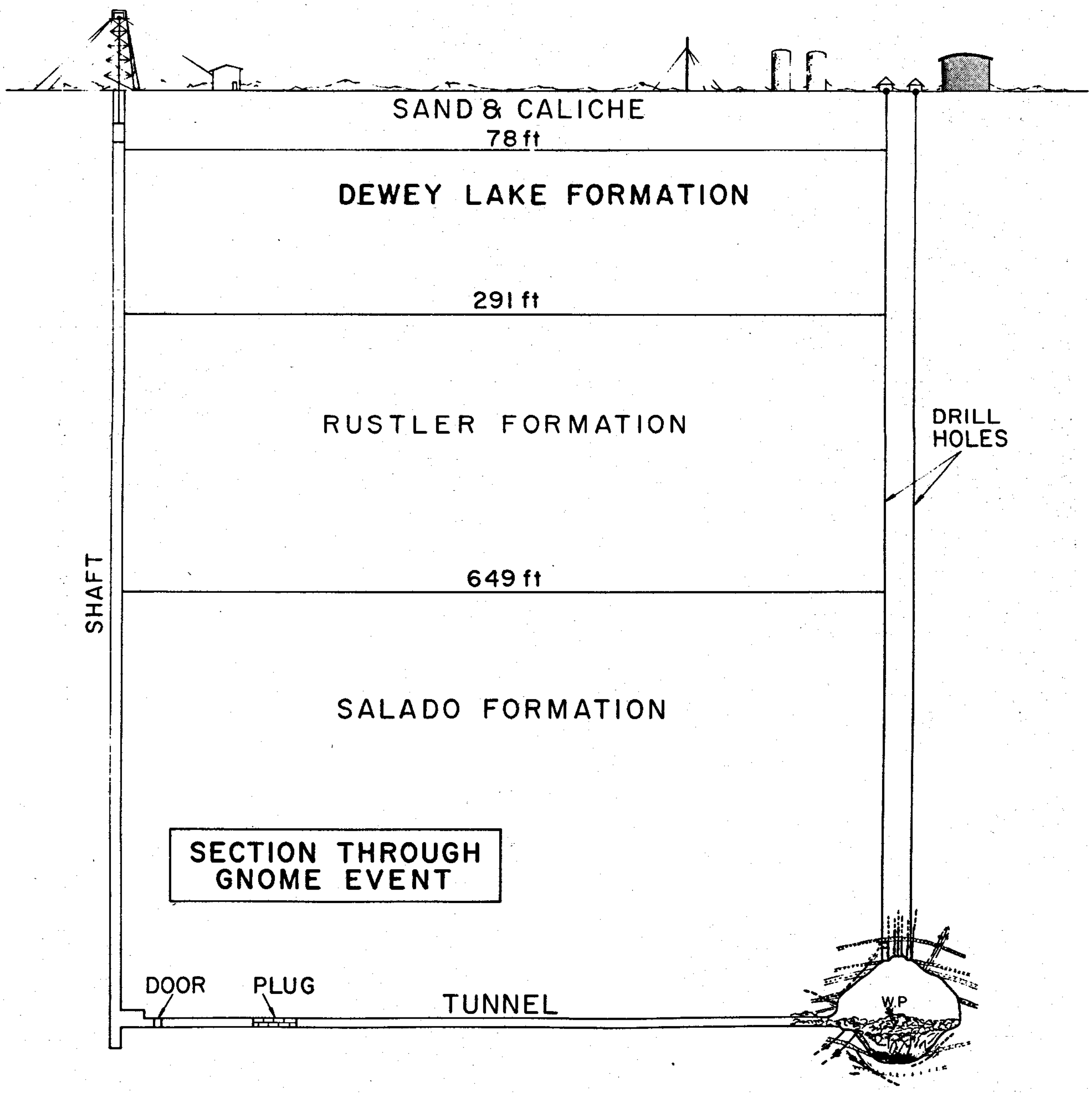

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Fig. 6. Section through the Gnome site.