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DIATREMES AND CRATERS ATTRIBUTED TO NATURAL EXPLOSIONS*

By

E. M. Shoemaker

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By E. M. Shoemaker

ABSTRACT

Diatremes - volcanic pipes attributed to explosion - and craters have been studied to infer the ultimate causes and physical conditions attending natural explosive processes.

Initial piercement of diatremes on the Navajo reservation, Arizona was probably along a fracture propagated by a high-pressure aqueous fluid. Gas rising at high velocity along the fracture would become converted to a gas-solid fluidized system by entrainment of wall-rock fragments. The first stages of widening of the vent are probably accomplished mainly by simple abrasion of the high-velocity fluidized system on the walls of the fracture. As the vent widens, its enlargement may be accelerated by inward spalling of the walls.

The inferred mechanics of the Navajo-Hopi diatremes is used to illustrate the possibility of diatreme formation over a molten salt mass.

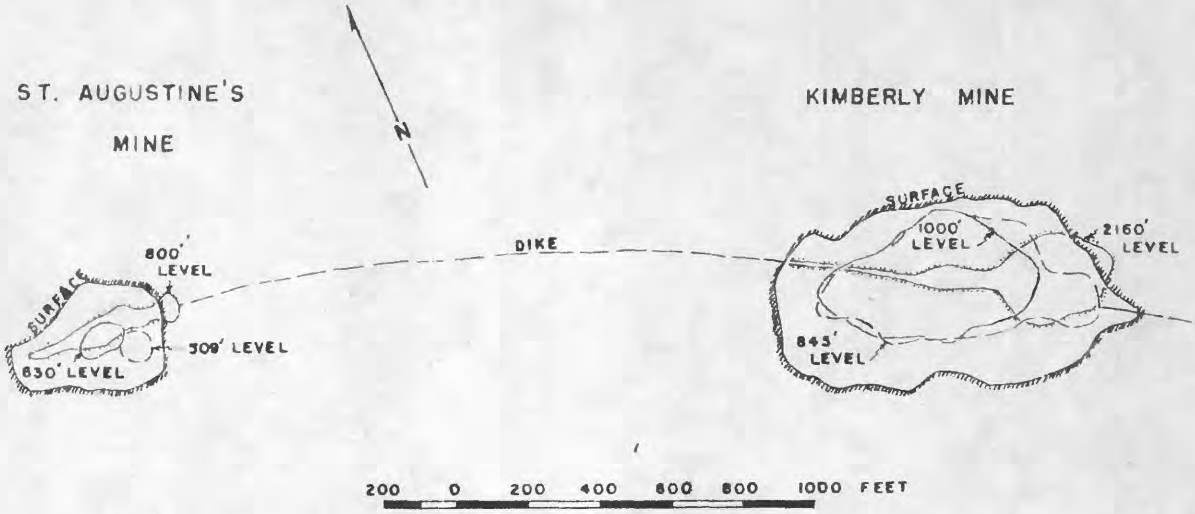
INTRODUCTION

A general investigation of diatremes (volcanic pipes attributed to explosion) and craters considered to be formed by natural explosion was begun in April 1956. The objectives of this study are to determine the mechanics of formation of those vents and craters which can be demonstrated to have originated directly or indirectly from explosive processes and, insofar as possible, infer the ultimate causes and physical conditions attending the explosive processes. Suggestions will be offered as to how the results obtained from this study may be applied to predict effects from large artificial underground explosions.

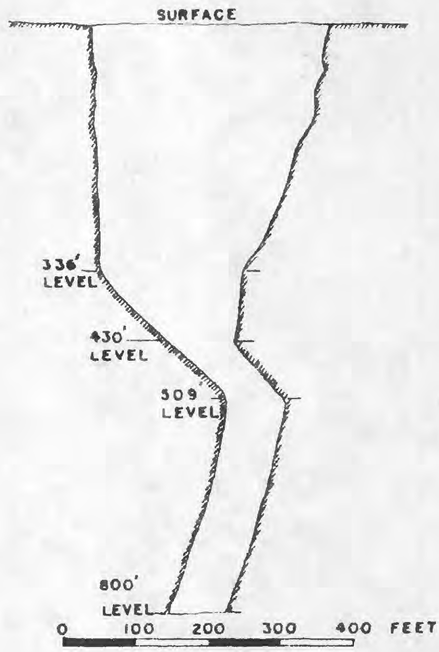
This work is part of a program that the U. S. Geological Survey is conducting in connection with its Investigations of Geologic Processes project on behalf of the Division of Research, U. S. Atomic Energy Commission.

GENERAL CHARACTER AND DISTRIBUTION OF DIATREMES AND NATURAL CRATERS

The classic examples of volcanic pipes to which the name diatreme has been attached (Daubreé, 1891) include the diamond pipes of South Africa (Wagner, 1914; Williams, 1932), the tuff pipes of the Schwabian Alb in Germany (Branco, 1894; Cloos, 1941) and the volcanic necks of East Fife, Scotland (Gieke, 1897 and 1902). A few of the diamond pipes have been completely explored over a large vertical range by mining operations (fig. 1). The diatremes are of irregular funnel shape in vertical section and, at any given level, roughly circular or elliptical to highly irregular in horizontal section. Some have been observed to pass downward into dikes. Most diatremes cut cleanly through the surrounding country rocks which are not noticeably deformed or displaced.



PLAN SHOWING CONTOURS OF KIMBERLY AND ST. AUGUSTINE PIPES
(AFTER WAGNER, 1914)



SECTION THROUGH ST. AUGUSTINE'S PIPE IN A NORTHWEST DIRECTION
(AFTER WAGNER, 1914)

FIGURE 1.--ST. AUGUSTINE'S AND KIMBERLY MINES, SO. AFRICA

The pipes are filled with a variable assortment of clastic debris, generally a complex mixture of fragments of older rocks torn from the walls of the vent and fragments of new igneous material. In some places the exposed clastic filling is distinctly bedded and has been deposited either by falling back of ejected material or subaqueously in an open vent near the surface. In other places the clastic filling is massive and has clearly been emplaced during the opening of the vent. Many of the fragments torn from the walls can be shown to have been derived both from below and from above the level at which they are found. Igneous rocks found in volcanic pipes to which Daubreé applied the name diatreme are of unusual basic composition and are noteworthy for higher-than-average concentrations of water.

Diatremes similar to the classic examples have a world-wide distribution but are most commonly found in plateau or platform parts of the continents. They are exceptionally abundant on the South African Plateau (Wagner, 1914; duToit, 1912) and are also known from India (Dubey and Sukumar, 1949), the Siberian platform (Menyailov, 1955), and the central United States (Rust, 1937; Miser and Ross, 1923). Some of the best-exposed examples of diatremes are found in the Colorado Plateau region of the United States (Hack, 1942; Shoemaker, 1956).

The surface expression of a newly formed diatreme is a crater surrounded by a low rim of ejected material and commonly occupied by a lake, which is referred to in the geologic literature as a maar. The most thoroughly studied maars and related craters are those of the Eifel region in the lower Rhine Valley of Germany (for a recent description see Hopmann, Frechen, and Knetsch, 1951), but they have also been described from the Auvergne region of France (Scrope, 1858), Burma (Burri and Huber, 1932), India (Malcolmson, 1840), Africa (Rohleder, 1936; Junner, 1937; Holmes, 1956), Mexico (Ordonez, 1900, 1905a, 1905b; Jahns, 1952), and the United States (Darton, 1905, 1916; Reiche, 1940; Russell, 1885).

Maar-type craters have frequently been confused with meteorite craters from which, in some cases, they may be distinguished only with considerable uncertainty. The larger meteorite craters offer, in themselves, excellent examples for study of the results of relatively shallow underground explosions. (For recent listings of probable meteorite craters see Hardy, 1954 and Leonard, 1956.) Craters of probable meteoritic origin on the moon may illustrate the results of explosions covering a very large range of energy that may extend as high as 10^{32} ergs or about 10^{10} megatons (Baldwin, 1949, p. 209-210).

Other structures associated with diatremes or that may be related to diatremes or are possibly produced by underground explosion include clastic or breccia dikes and pipes (Farmin, 1934; Fairbairn and Robson, 1942; Walton and O'Sullivan, 1950; Tweto, 1951; Reynolds, 1954) cryptovolcanic structures (Branco and Fraas, 1905; Kranz, 1914; Bucher, 1936), and various crackled or brecciated intrusions (Gilluly, 1946; Butler and Vanderwilt, 1933).

SERPENTINE-BEARING DIATREMES OF THE NORTHERN NAVAJO INDIAN RESERVATION, ARIZONA AND UTAH

Detailed field work has been started on four serpentine-bearing diatremes in the northern part of the Navajo Indian Reservation which illustrate a variety of structures produced by natural explosion (fig. 2). In shape the vents vary from a roughly elliptical pipe or funnel about one-fourth by one-half mile across to an elongate sinuous dike-like opening one or two hundred yards in width and several miles long. One is localized along a nearly vertical dike, whereas from another vent a nearly horizontal tongue or sheet of serpentine and clastic debris extends for half a mile along the bedding of the enclosing country rock.

The material filling the vents is a heterogeneous aggregate composed mainly of fragments of the country rock (rock pierced by the vents) in a matrix of comminuted serpentine ($3[Mg,Fe]O \cdot 2SiO_2 \cdot 2H_2O$). The serpentine is apparently a remnant of the explosive agent active in the formation of the vents, but it is not known whether the serpentine particles have crystallized partly from the fluid state or whether excess water and perhaps other volatile constituents may have been explosively released from or through serpentine or a more hydrous heteromorph in the solid state.

Rock fragments enclosed in the serpentine range in size from microscopic particles to huge blocks several hundred feet across. All parts of the stratigraphic section pierced by the vents are represented among the fragments as well as a great variety of crystalline rocks derived from the basement complex that underlies the sedimentary sequence of this region. The sources of the fragments found at any one exposure have a vertical range of 7,000 or 8,000 feet in the stratigraphic section and probably at least several miles in the basement complex. The ultimate source of the serpentine is not known but may lie near the base of the crust (about 20 miles deep in this region, Tatel and Tuve, 1955) or lower. Small rock fragments are derived from horizons both above and below the level at which they are found in the vent, but, with the exception of the Mules Ear diatreme, fragments greater than 10 or 20 feet across are generally derived from above.

In the Mules Ear diatreme there is a crude zonal distribution of materials according to their source. Several pipe-like masses, composed mainly of serpentine and small crystalline rock fragments derived from great depth, occur in the center of the vent. Around these "pipes" is an irregular zone made up mainly of fragments of sedimentary rocks and only minor amounts of serpentine and crystalline rock debris in which a large part of the clastic material has been derived from depths of a few hundred to a few thousand feet. Between this zone and the wall of the diatreme the vent is also filled mainly with fragments of sedimentary rocks, but the majority of large blocks have been derived from strata several thousand feet higher than the level of exposure.

Most fragments in the diatremes derived from above are angular but many have polished and striated faces. The fragments derived from below are more commonly rounded, especially the hard crystalline rocks derived from great depths, though some small pieces are faceted. Nearly all fragments derived from great depth are polished and some are striated. Locally the walls of the vents are also polished and striated.

The structure of the rocks surrounding the diatremes shows clearly that the space occupied by the vents has not been created by thrusting aside of the walls but rather by excavation and removal of the country rock.

MECHANICS OF FORMATION OF A NAVAJO TYPE OF DIATREME

The physical reaction underlying most, if not all, explosive volcanism appears to be the rapid to violent boiling of an aqueous solution or exsolution of a gaseous phase (in many cases probably a supercritical fluid) from a magma (a rock melt with or without suspended solid phases) (Perrett, 1924) or possibly, as may be true for serpentine, from solid rock. Normally the gas phase formed is probably composed mainly of water, though carbon dioxide and other volatile rock constituents may be important in some. In some volcanic explosions the water is apparently derived from ordinary ground water which has either become heated by contact with magma or surrounding heated rocks, as is true for rare explosive volcanism in Hawaii (Jaggar and Finch, 1924; Stearns, 1925), or been dissolved by the magma and subsequently exsolved. In other explosions the water may be an inherent constituent of the magma, as seems likely for the typical diatremes.

Exsolution of a gaseous phase from a magma would be expected to begin whenever the pressure on the magma falls below that required to keep the volatile constituents in solution. This phenomenon could be brought about by relief of the lithostatic pressure by regional stresses in the earth's crust, by upward migration of magma into a zone of lower pressure, or by shift of the phase equilibrium boundary due to crystallization or drop in temperature of the magma (retrograde boiling).

If it be supposed that under the Navajo Reservation water-saturated serpentine magma or solid plastic serpentine were ascending into the earth's crust along pre-existing fractures or lines of structural weakness, just prior to diatreme formation, the stage would be set for explosive eruptions. A level would ultimately be reached by an ascending intrusion where the pressure of the superincumbent rocks was sufficiently low for exsolution of gas to begin. If sufficient gas or supercritical fluid were evolved, a fracture would be propagated to the surface through which the gas would escape. The resultant drop in pressure accompanied by vesiculation or disintegration in the upper part of the intrusion could permit boiling to begin in successively lower and lower parts of the intrusion until some limiting depth were reached at which the pressure at the base of the fluidized column became equal to the vapor pressure of the serpentine intrusion. The mechanism envisioned is closely comparable in several respects to that of a geyser.

It is not known whether the serpentine-bearing diatremes were formed by one or multiple explosions, though there is clear evidence of multiple explosions in other diatremes on the Navajo Reservation. The only diatreme whose birth is known to have been witnessed and described by a geologist (Mueller, 1956) broke out in 1955 at Riñinahue, Chile and was active intermittently for a period of three months. Periods of complete inactivity lasting for days were broken by violent eruptions of about 20-minutes duration in which volcanic ash and small rock fragments were thrown up to heights of about 7 kilometers.

The initial piercement of most of the Navajo diatremes, regardless of the ultimate shape of the vent, was probably along a more or less planar fracture of relatively short lateral and either small or great vertical extent. Both the volcano at Parícutin, Mexico (Foshag and Gonzalez, 1956) and evidently the Riñinahue diatreme broke out through linear fissures. The propagation of the fracture by high-pressure gas or fluid is analogous to the formation of artificial hydraulic fracture systems induced in certain oil-well operations (Odé, 1956; Anderson, 1951, p. 22-28, 146-154). Depending on the supply and viscosity of the fluid the fracture may be propagated very rapidly.

Once the fracture is opened the gas may move along it at high velocity. Bits of serpentine and fragments of rock plucked from the walls of the fracture would become entrained converting the simple gas phase to a gas-solid fluidized system similar to some of the small-scale fluidized systems of the chemical industries (Matheson, Herbst, Holt, and others, 1949). The intricate mixing, rounding, and polishing of the debris in the diatremes strongly indicate fluidization. The first stages of widening of the vent are probably accomplished mainly by simple abrasion of the high-velocity fluidized system on the walls of the fracture. The development of the small diatreme at Red Mesa (fig. 2) appears to have been arrested at about this stage.

As the vent widens a secondary process comes into play. Owing to a pressure drop across the wall of the vent the wall will tend to spall inward. At great depths the spalling may be sudden and violent as in the case of rock bursts in deep mines, but near the surface the spalling may be no more than gentle slumping. Depending on the velocity and density of the fluidized system, large blocks spalled from the walls of the vent may tend to rise or sink. The distribution of material in the Mules Ear diatreme (fig. 2) might be explained by a velocity gradient between the center and walls of the vent. In the later stages of development, as represented at Mules Ear, spalling and slumping may become the dominant process in widening the vent.

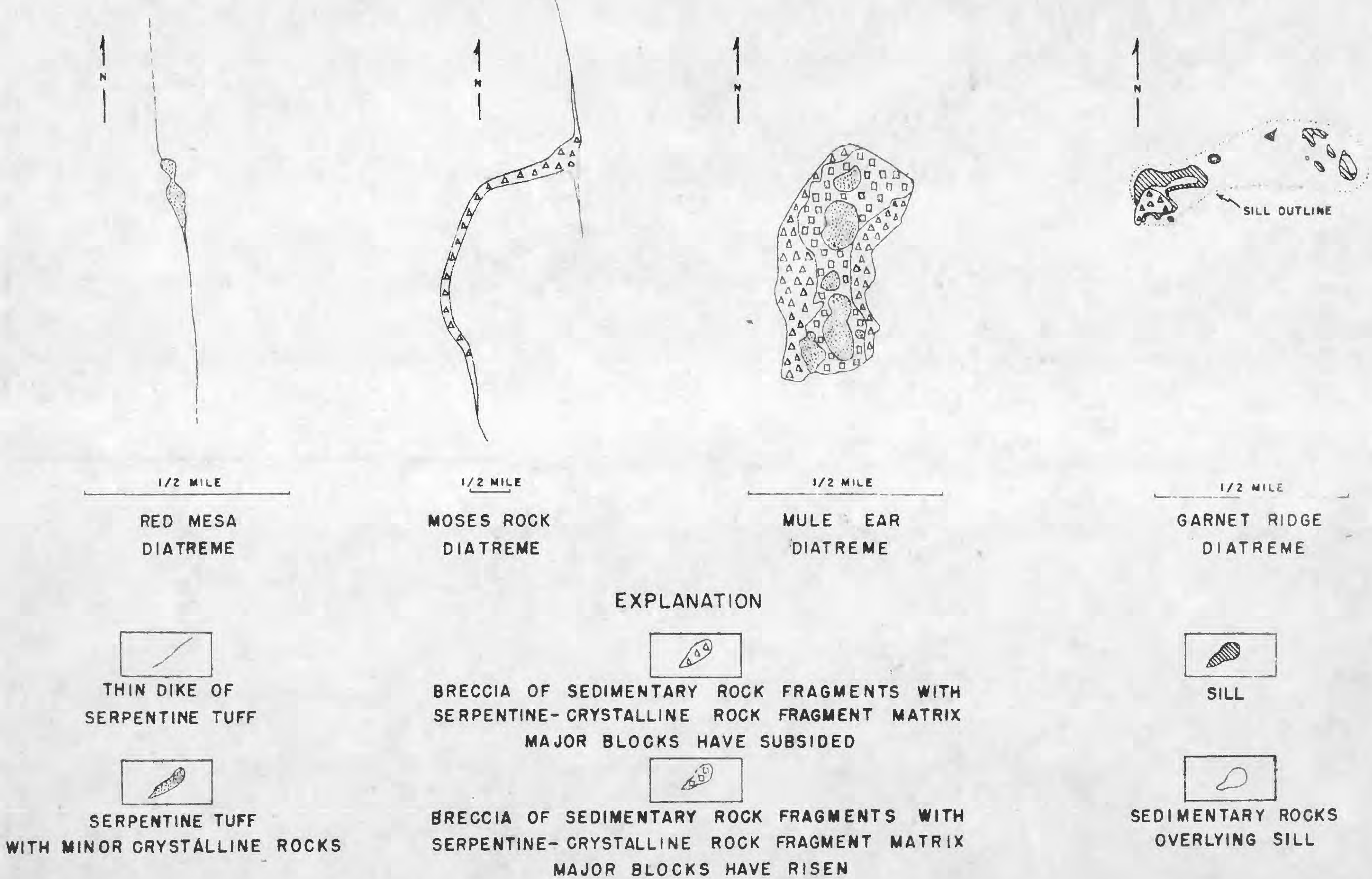


Figure 2.--DIAGRAMMATIC PLAN VIEWS OF FOUR SERPENTINE-BEARING DIATREMES IN THE NORTHERN NAVAJO INDIAN RESERVATION

FORMATION OF A NAVAJO TYPE OF DIATREME OVER A MOLTEN SALT MASS

On the basis of the foregoing working hypotheses, the possibilities may be tentatively evaluated for piercement and formation of a Navajo type of diatreme over a molten salt mass produced by a contained megaton explosion. It will be assumed here that the explosion is sufficiently deep for the formation of a camouflet _/. The mechanics of cratering due

_/ "Underground cavity caused by an underground explosion which fails to rupture the surface of the earth." Special Regulation 320-5-1, 1950, Dictionary of United States Army Terms.

to shallow explosion are different from those of formation of the diatremes described and will not be considered here. The phenomena discussed will be those occurring after the dissipation of the original shock and seismic waves.

Starting at high temperature and pressure there are two regions or fields in the theoretical temperature-pressure-concentration phase equilibrium diagram for a binary system such as salt and water (Roozeboom, 1904; see, for example, Findlay, Campbell, and Smith, 1951, p. 250-254) that are likely to be intersected by cooling or lowering the pressure on a hydrous molten salt mass, in which a gas would be formed by exsolution from a liquid. The first of these, adjacent to the critial curve, is a region of two fluids, one gaseous, the other liquid. The second is a field of one gaseous phase and one solid phase and is adjacent to a field of one liquid phase and one solid phase.

The experimentally determined phase equilibrium diagrams of Keevil (1942) (see also Morey and Chen, 1956) define the conditions of pressure, temperature, and composition of an $NaCl-H_2O$ system for boiling at pressures and temperatures near the three-phase boundary (salt, liquid, and vapor) (fig. 3). At pressures greater than 389 atmospheres (about 5,900 feet depth in salt) no boiling will occur. Retrograde boiling will begin (under equilibrium conditions) at a pressure of 389 atmospheres and a temperature of 600° C. from a solution containing 59.9 percent H_2O. At a pressure of about 370 atmospheres (depth of about 5,600 feet) boiling will begin at a temperature of 646° C. on the high-temperature (or high-salt) side of the pressure maximum from a solution containing 49.5 percent water. Starting from the pure salt side of the diagram, the higher the pressure the higher the water concentration of the liquid phase required for boiling, up to the 389-atmosphere maximum. The concentration of water in natural bodies of salt is too low for boiling to occur at the three-phase boundary under lithostatic pressure at depths that are even rather small fractions of the depths probably required to contain a megaton explosion. If it should prove desirable to introduce diatreme formation in the later stages of cooling, water or some other volatile will probably have to be added to the system.

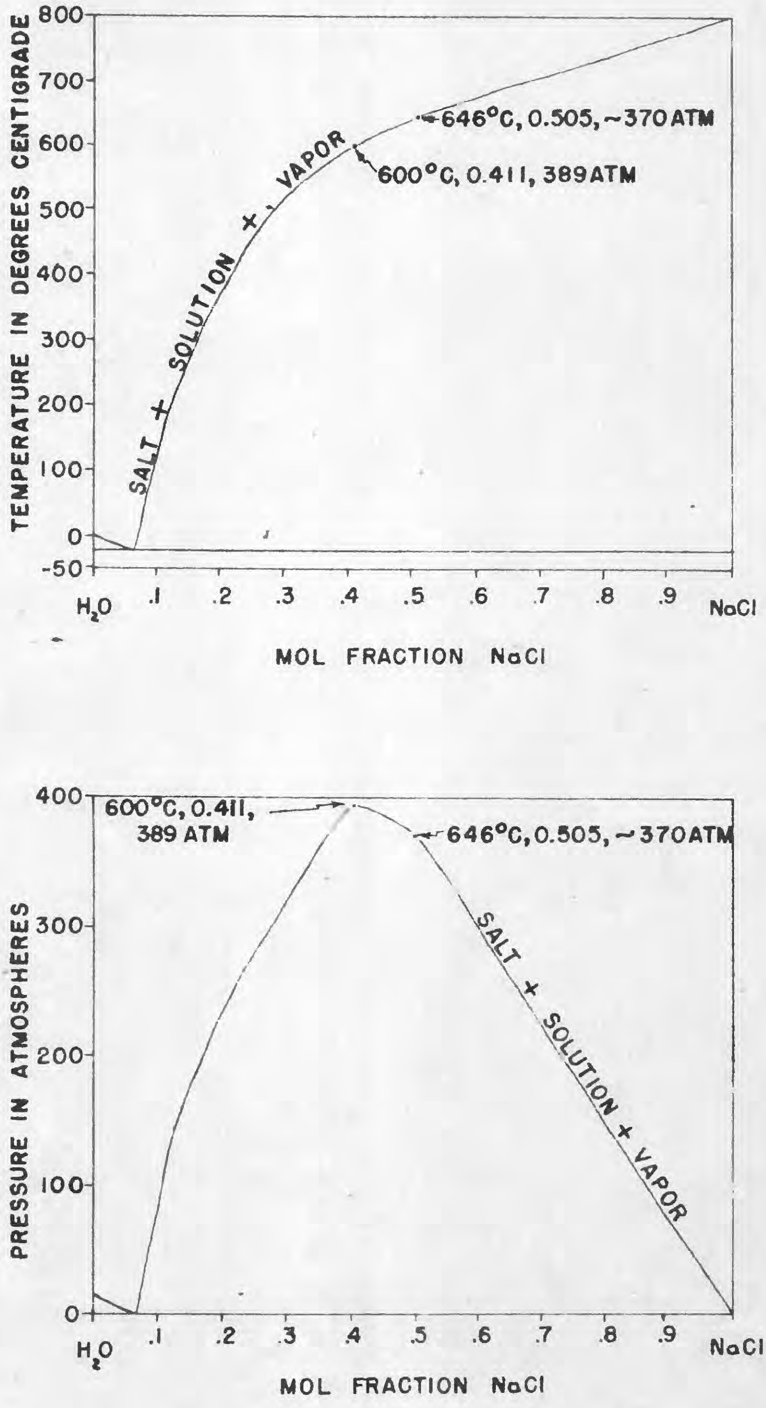


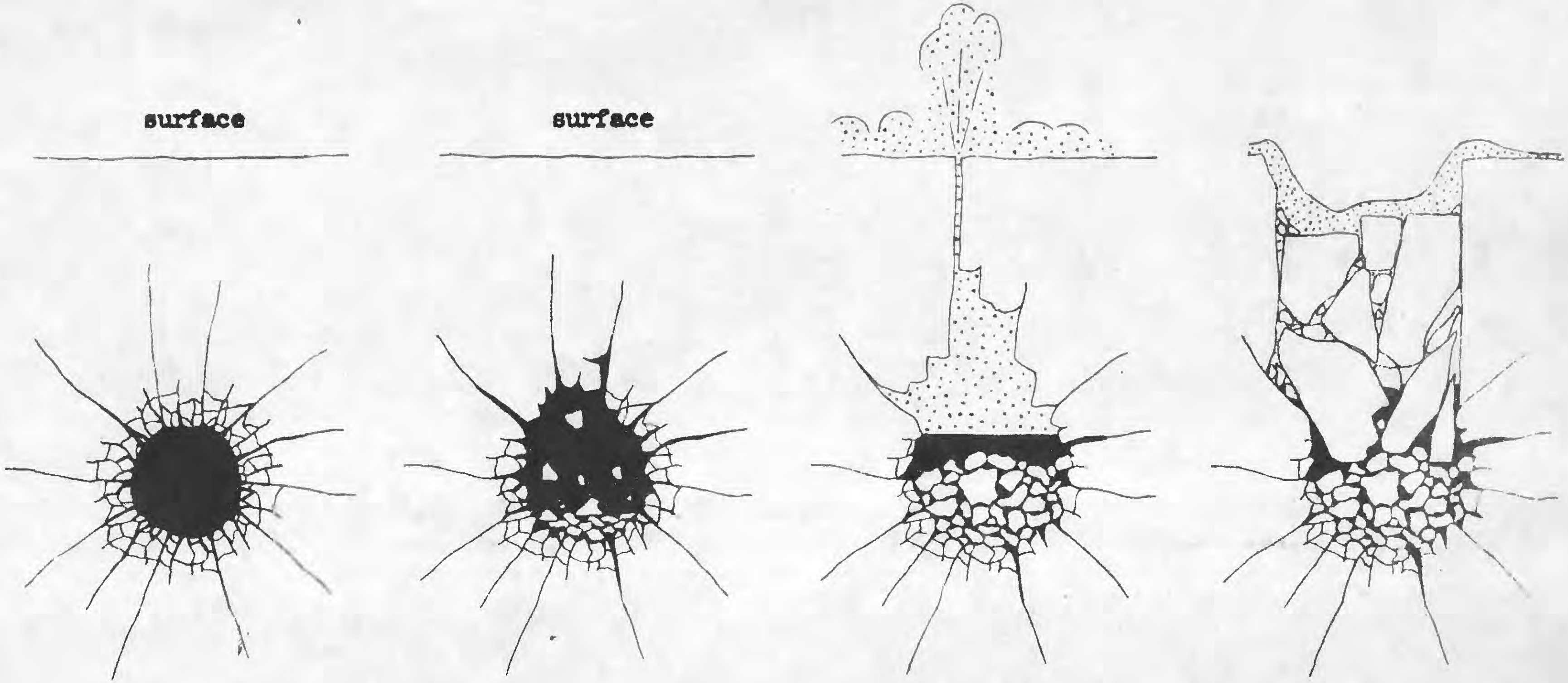
Figure 3--VAPOR PRESSURE OF AQUEOUS SOLUTIONS AT HIGH TEMPERATURE (AFTER KEEVIL, 1942)

The thermodynamic history of a molten salt mass formed by the shock wave from a megaton explosion in salt would probably run along the following lines. An initial thermal gradient from center to margin of the molten mass would rapidly be eradicated by convection. At this stage the molten mass would have considerable superheat (would be out of phase equilibrium with its walls). If the temperature of the melt were above the critical temperature, any drop in pressure would be accompanied by expansion of the system and conditions would be ripe for the formation of a diatreme. If the temperature of the melt were below the critical temperature and if the system contained a few percent of a volatile constituent such as water, the system either would be in the gas-liquid two-phase field of the equilibrium diagram (neglecting all minor constituents), or a drop in pressure could lower the system into this field. If the melt should stope its way or otherwise penetrate to a region of sufficiently low confining pressure, conditions would again be ripe for the formation of a diatreme.

Meanwhile the melt will dissolve its walls, enlarging the molten system and tending toward thermodynamic equilibrium with the solid salt. Should eruption not intervene, continued solution of salt and conduction of heat away from the melt will ultimately bring the system into the liquid-solid salt two-phase field. If the system is composed of salt and water and the molten mass were never to migrate into a region of pressure less than 389 atmospheres, it could be considered safe from diatreme eruption. Below 389 atmospheres, however, the onset of eruption due to intersection with the three-phase boundary could be brought about either by upward migration of the melt or by crystallization of salt during cooling.

The geometry of a molten mass produced by the explosion of a megaton device in salt is likely to be complex soon after the detonation. Small-scale explosions in rock produce shattered zones surrounded by a radiating system of fractures. Powdered rock is injected along the fractures. Rock in the walls of any camouflet formed around a megaton explosion will be severely deformed, and a camouflet will probably be surrounded by a fracture system propagated during passage of the shock wave. Part of the melt is likely to be injected along the fracture system. The shattered roof of a cavity in salt of the order of 1,000 feet across is not likely to be self-supporting. If the volume of the camouflet is greater than the volume of the melt soon formed, the roof will tend to cave in and the cavity and melt to migrate upward. If the melt is completely enclosed by solid salt, the melt will also tend to stope blocks from the roof and migrate upward.

Whenever a finger or projection of the melt reaches a region where the confining pressure is equal to or just less than the vapor pressure of the fluid system, a diatreme could be expected to form if there are sufficient contained volatiles. Under appropriate conditions nearly the whole molten mass or a major part of it could spew forth as a froth at the surface, leaving an empty chamber underground that would eventually collapse. (See fig. 4.) The process would be essentially a small-scale version of the formation of calderas depicted by Williams (1941, p. 334-338) or of the much smaller craters of the Pinacate region, Sonora, as described by Jahns (1952a, 1952b). Without appreciable volatiles in the system it is also possible that the melt would stope its way quietly to the surface without the intervention of explosive eruption.



(1) Detonation of megaton device in a salt plug produces roughly spherical mass of molten salt surrounded by fractured solid salt.

(2) Molten mass begins to stope fractured roof and migrate upward. Superheat allows volume of melt to grow.

(3) Uppermost projection of melt reaches level where vapor pressure of melt exceeds lithostatic pressure. Diatreme forms and melt chamber is partially drained.

(4) With loss of support the roof of the melt chamber caves, forming crater at surface of ground blanketed with a deposit of vesicular salt fragments.

Figure 4.--Hypothetical development of a diatreme over a hydrous salt mass.

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