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CAVITATION AS A GEOLOGICAL AGENT

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ABSTRACT. Cavitation is the formation and collapse of bubbles of vapor in a fluid stream. Formation of the bubbles is caused by a local reduction in absolute pressure to the vapor pressure of the fluid; collapse of the bubbles is caused by a subsequent pressure increase. The pressure reduction is usually caused by an increase in local velocity due to an irregular streamline configuration (Bernoulli's Theorem). The mechanism is important because the powerful shock waves initiated by the collapse (i.e., implosion) of the bubbles cause rapid erosion of even the hardest materials. For example, cavitation eroded to a maximum depth of 18 inches of concrete in a dam spillway in 23 hours.

Although many complex variables affect cavitation, each is sufficiently well known to predict natural occurrences on a semi-quantitative basis. In an open stream, cavitation would be expected to begin at velocities of 25 to 30 feet per second.

Cavitation may be an important agent in the erosion of rock by glacial meltwaters and by high velocity streams. In a hydrothermal environment, cavitation is probably only a very rare phenomenon and of little importance.

INTRODUCTION

The purpose of this paper is to bring to the attention of geologists the mechanism and occurrences of cavitation and to suggest its possibilities as an agent in diverse geological phenomena.

In most phases of hydraulic engineering cavitation presents a serious problem; therefore, much pertinent material on the subject may be found in engineering publications. With the notable exception of Hjulström's paper (1935), geological papers in general do not mention cavitation. In the following discussion, the mechanism of cavitation in water is examined in reference to stream erosion. The principles are readily applicable to other fluids and to other processes, a few of which are considered superficially in the conclusion.

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BASIC MECHANISM

Elementary studies of fluid flow show that there is a reduction in pressure with an increase in velocity (Bernoulli's Theorem) in a fluid stream. If the velocity is sufficiently great, the pressure drops to the vapor pressure of water and "steam" can form. This "steam" or water vapor occurs as small bubbles, a fraction of a centimeter in diameter, which form at the point where this critical pressure is reached. These bubbles are rarely formed individually but usually occur as aggregates, giving the water the appearance of foaming. The bubbles may then either be carried away in the stream or become momentarily lodged against the walls or any solid material. In either event, if there is a slight increase in pressure the bubbles are then unstable and collapse very quickly and violently. The collapse of a bubble in contact with solid material produces a hammer-like blow of great strength on a very small area. If the bubble collapses in the stream, violent shock waves are produced; these rapidly dissipate unless they come in contact with solid material, where they may pound on the surface. At present the experimental difficulties involved in the measurement of the instantaneous and very local pressure from a bubble collapse have not been conquered, but experimental results recently gave 30,000 atmospheres as a minimum pressure (Vennard and Lomax, 1950). The large order of magnitude of the pressure is very significant for the understanding of cavitation erosion. The effect of these "hammer blows" is to shatter the surface of any nearby solid material; then pieces become dislodged and are carried away as the fracturing continues and surface roughness increases. The erosion of the viewing windows of experimental cavitation chambers is described by Rasmussen (1949, p. 44): "The glass is first penetrated by a fine network of cracks, then particles of the surface come loose, and gradually the glass assumes a 'frosted' appearance."

The rate of erosion is generally dependent on the smoothness of the walls; the smoother the walls, the greater the resistance to cavitation. The rate of erosion would therefore accelerate as erosion continued, because of the increased roughness. This increase in the rate of erosion has been noted in engineering projects which have become suddenly threatened by cavitation. In an extreme example, concrete exposed to cavitation in a dam spillway during one test eroded to a maximum depth of 18 inches in 23 hours (Ball, *in* Discussion of Symposium, 1947, p. 92).

Rasmussen (1949, p. 40) states that some erosion occurs also at the point of formation of the bubbles, but other authors do not concur and, if such erosion does take place, the cause is in doubt. The cause of the erosion of the walls at the area of collapse of the bubbles is now generally considered to be primarily mechanical and is directly due either to the pressure waves or to the collapse of the bubble in contact with the walls (Rasmussen, 1949, and Vennard *in* Symposium, 1947). Vibration induced by successive impacts probably causes appreciable failure through fatigue. A minor electrical and chemical effect is also known, and there may be other unknown effects. A temperature rise has been noted at the collapse of individual bubbles. The temperature at the collapse of a bubble has been calculated at 2700° K (Rutenbeck, 1941), and cavitation erosion with the appearance of fusion in test samples has been cited (Nowotny, 1942; Rutenbeck, 1941) as proof of the high temperatures at the point of collapse. The author has observed carbon-coated gobular forms due to fusion on an iron surface and the odor of burning rubber where each has been exposed to cavitation. The temperature has not been measured experimentally because, like the high pressure, the high temperature is only very local and instantaneous. This local high temperature at the collapse of a bubble would tend to form another bubble by evaporating more vapor. High speed motion pictures show a cyclic collapse and regrowth of bubbles (with decreasing size downstream) (Knapp, 1952); therefore, the temperature increase is probably important in increasing the number of impacts from bubble collapse by reforming collapsed bubbles.

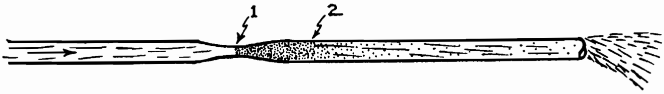


Fig. 1. Cavitation in water flowing through a Venturi tube. (1) Area of minimum pressure and most rapid bubble development (foaming). (2) Area of greatest erosion (variable with velocity, pressure, etc.) caused by the statistically greatest number of bubbles collapsing.

Note: Cavitation may be produced in the laboratory by water flowing through a small constricted glass tube. A 5 mm glass tube constricted to about 2 mm and connected to a faucet by rubber tubing produces visible cavitation if the water flow is adjusted for the maximum effect. Essentially the same effect may be attained by gently squeezing a rubber tube with water flowing through it.

FACTORS AFFECTING BUBBLE FORMATION

Cavitation may be divided into two types called "burbling cavitation" and "laminar cavitation" (Edstrand, 1946). Burbling cavitation is characterized by simple groups of bubbles whereas laminar cavitation is characterized by long, pipe-shaped eddies with pipe-shaped bubbles at the axes of the eddies. The two types of cavitation may occur together, one or the other type predominating.

Because the erosion of the walls near the bubble collapse is essentially due to the implosion or shock waves from the sudden filling of the vacuum previously filled by the vapor, anything that would tend to reduce the incompressibility of water would reduce both the impact of the bubble collapse and the efficiency of transmission of the shock waves by acting as a "cushion." Air entrapped in water, either dissolved or suspended as bubbles, is drawn into the low pressure centers and enters the cavitation bubbles. The air in the bubble acts as a cushion when collapse does take place. According to Rasmussen, (1949, p. 56) about three-tenths of one percent air by volume reduces cavitation erosion to a minor or negligible phenomenon, regardless of the type of cavitation involved. The explanation is readily apparent when the compressibility of water is considered. A change in pressure causes an inversely proportional change in volume; for a one atmosphere change in pressure, the ratio of volume increment to original volume is 1 to 20,000 for pure water, but the ratio for water with 0.1 percent air by volume is 10 to 20,000 or ten times the compressibility of pure water (Rasmussen, 1949, p. 4).

Natural stream water contains various amounts of oxygen, nitrogen, argon, and carbonic acid (Hjulström, 1935, p. 307), but probably not in sufficient quantities under most conditions to reduce cavitation appreciably in a homogeneous stream. Experimental measurements have been made of the internal bubble pressure; pressures higher than the vapor pressure have been noted and interpreted as bubbles of gas taken from solution (Vennard *in* Symposium, 1947), but the usual measurement matched the vapor pressure very well. The close correlation between measured pressure and vapor pressure proves that the content of the bubbles is nearly all water vapor (Knapp and Hollander, 1948, p. 422).

For a slight increase in pressure to cause the violent collapse of the vapor bubbles in cavitation, there must be essentially instantaneous attainment of equilibrium between the vapor and liquid phases after a pressure change.

The slower the rate of attainment of equilibrium, the more the bubble collapse is cushioned and the less violent is the shock wave produced. The rate of approach to equilibrium depends on the difference between the vapor pressure and absolute pressure (other factors remaining constant). In other words, the more unstable the vapor under normal stream conditions the faster and more violent the collapse. It is also more difficult (i.e., it requires higher velocity) to form vapor bubbles under these conditions. Consequently, higher vapor pressure has the dual effect of increasing the number of vapor bubbles formed (Nowotny, 1942, p. 17) and decreasing the violence of each collapse. Since the rate of erosion depends on both the violence of each collapse and the number of bubbles collapsing (temporarily ignoring other factors), it is evident that there is an optimum range of vapor pressures at any specific absolute pressure for maximum rate of erosion. The vapor pressure is fixed by the temperature; therefore, we shall refer to the temperature instead of vapor pressure, because it is the more easily measured variable.

For a pressure of one atmosphere, Nowotny (1942, p. 12) gives the optimum temperature range of 55°-70°C. (131°-158°F.), but the efficiency of

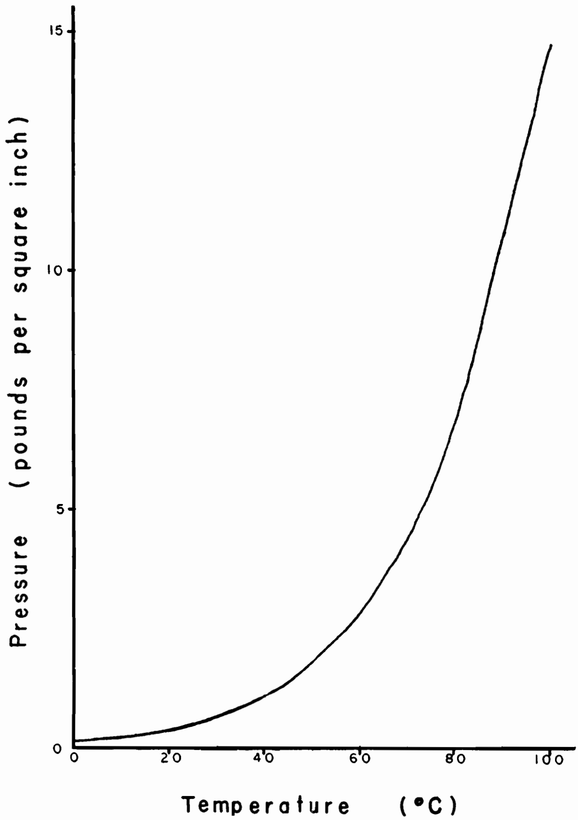


Fig. 2. Relation of vapor pressure of water to temperature. (Data recalculated from Rouse, 1950, p. 364.)

cavitation falls off rapidly only as the absolute pressure is approached by the vapor pressure, i.e., near 100°C. Probably the main reason for the reduction of erosion efficiency at high temperatures is simply that vapor pressure is an exponential function of temperature (fig. 2); at higher temperatures the vapor pressure increases more rapidly with temperature and reduces more rapidly the gradient between the vapor and absolute pressures.

Evidently the vapor pressure of the water is of primary importance to the formation of the bubbles, because the pressure at some place in the stream must drop to this critical pressure before water can convert from the liquid to the gaseous state and form bubbles. Figure 2 shows the variation of vapor pressure with temperature. Atmospheric pressure in general decreases about 0.45 pounds per square inch per thousand feet increase in elevation. The optimum condition for cavitation, with the highest vapor pressure within previously discussed limits and lowest atmospheric pressure, occurs at high temperatures and at high elevations. In other words, the conditions that require the least pressure reduction through increase of stream velocity, in order to form the vapor bubbles, are at high altitudes and high temperatures, although cavitation does occur more commonly under the less favorable conditions at sea level and relatively low temperatures.

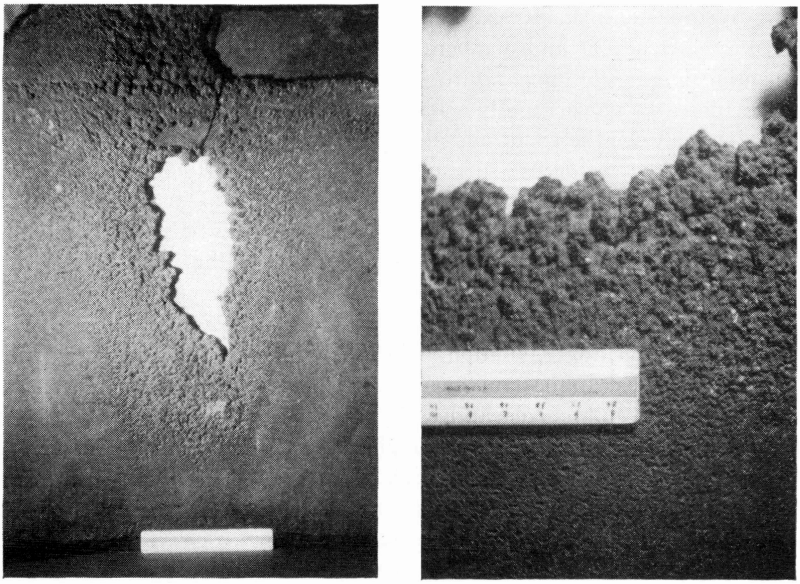
The pressure of only a small part of a stream ever drops to the vapor pressure. The actual triggering of bubble formation takes place at a constriction or a bend in stream flow lines where the velocity is increased for a short distance. A low pressure area is frequently noted at the wall on the concave side (in plan view) of the stream as, for example, at the wall near constrictions. Low pressures also occur at the center of eddies. Diagrams of several low pressure areas for typical stream line configurations, have been presented by Vennard (Symposium, 1947, p. 3).

Other properties of water which have a minor effect on the bubble formation are surface tension, viscosity, and heat of vaporization. Higher surface tension and viscosity oppose the formation of large bubbles, but high surface tension also increases the violence of the bubble collapse (Nowotny, 1942). Very high viscosity tends to prevent all cavitation because there is a hydrodynamic tendency towards "sheeting" in flow around an obstacle, and no vapor bubbles are formed. A high heat of vaporization hinders the bubble formation because a greater concentration of energy is necessary to form each bubble but the collapse would probably be more violent with the release of more energy. The properties of surface tension, viscosity, and heat of vaporization together are insignificant in magnitude of effect on bubble formation in comparison with the effect of vapor pressure (Nowotny, 1942.)

FACTORS AFFECTING STREAM VELOCITY

Since the viscosity of water decreases with increasing temperature, it is obvious that the same stream will flow with greater velocity when warm than when cold. Eisenlohr (1948) has shown that this effect is measurable on the Kootenai River in Idaho. Although the mean stream velocity increases with decreasing viscosity, the magnitude of the velocity change is very small and is insignificant in comparison with the magnitude of the effect of temperature

PLATE 1



A B

Cavitation erosion of a steel plate.

A. A hole through a 5/8 in. steel conduit segment from the Ross Dam outlets. Note that the underlying patch is also pitted. The direction of flow was vertical from top to bottom. The scale is 6 in. long. (Photo taken at the Bureau of Reclamation Laboratories, Denver, Colorado.)

B. Detail of the globular forms on the eroded steel surface of A. Numbered divisions on the scale are inches above and half-inches below. (Photo taken at the Bureau of Reclamation Laboratories, Denver, Colorado.)

on the vapor pressure in considerations of cavitation over short distances. It should be noted, however, that with increasing temperature the decrease in viscosity and the increase in vapor pressure have an additive effect in promoting cavitation in a stream.

A limitation on the minimum size of a high velocity stream is necessary for the occurrence of cavitation. The stream must flow as a homogeneous fluid body without breaking up into streams of drops. For example, a high waterfall of small discharge will often break up into drops while a waterfall of larger discharge will maintain an undispersed fluid stream. The maximum velocity of a dispersed flow is approximately the same as the maximum velocity of falling drops, i.e., about 25 feet per second for still air. The maximum theoretical velocity for open channel flow in contact with the banks and bottom and flowing under one atmosphere pressure is about 73 feet per second (Hjulström, 1935, p. 290). As shown below, cavitation probably does not often take place at velocities as low as 25 feet per second but would most certainly take place in any stream near a velocity of 73 feet per second, unless the walls were extremely smooth and regular.

The cross-sectional velocity distribution of a stream of very high velocity ("shooting flow") is fairly uniform except near the margins where a thin layer of laminar flow takes place. The bed roughness in most natural streams is important in that the projections from the rough bed pass through the laminar zone into the area of shooting flow, causing a sharp change in streamline configuration which may trigger bubble formation. A hemispherical projection into the stream flow causes a local velocity (at a point where the tangent plane is parallel to the normal stream lines) approximately 1.5 times the mean stream velocity (Rouse, 1950, p. 32). Other shapes of projections may cause local velocities greater than 2.4 times the mean stream velocity. This large variation in possible local velocity emphasizes the importance of the streamline configuration and its ability to increase the velocity at a point where cavitation might occur to more than 240 percent of the mean stream velocity.

In order to give an estimate of the channel slope required for the velocities necessary to produce cavitation, the following approximate calculations based on Bernoulli's equation are presented. This equation is not exact for this type of flow, but it gives results of the correct order of magnitude. The following conditions are assumed:

velocity distribution: constant velocity over the normal stream cross section
streamline configuration: local velocity at cavitation point (v_2) = 2 x mean stream velocity (v_1)
water temperature: 70°F. (vapor pressure = 0.36 lbs. per sq. in.)
surface pressure: 14.7 lbs. per sq. in. (sea level atmospheric pressure)
air content of water: insignificant
stream flow: as a homogeneous fluid (undispersed)

$$\frac{v_1^2}{2g} + \frac{p_1}{\gamma} + z_1 = \frac{v_2^2}{2g} + \frac{p_2}{\gamma} + z_2$$

v_1 = mean stream velocity
p_1 = absolute pressure = 14.7 lbs. per sq. in.
z_1 = elevation of stream surface (stream depth)
v_2 = velocity at cavitation point (channel bottom) = $2v_1$
p_2 = vapor pressure = 0.36 lbs. per sq. in.
z_2 = elevation of stream bottom = 0 (assumed datum)
γ = specific weight of water = 62.4 lbs. per cubic ft.
g = acceleration of gravity = 32.2 ft per sec^2

Converting all terms to ft-lbs.-sec units and evaluating:

$$\frac{14.7 \times 144}{62.4} + z_1 = \frac{3v_1^2}{2g} + \frac{0.36 \times 144}{62.4}.$$

$$v_1 = 4.6\,(33.1 + z_1)^{1/2}$$

This equation shows the relation for the velocity necessary for cavitation to occur at any particular depth under the conditions assumed above. Note that this velocity is the mean velocity necessary for the stream flow since the local velocity due to the streamline configuration has been assumed equal to twice this mean velocity.

The derived equation gives the following conditions for the initiation of cavitation:

Depth (ft)	2.9	15.9	30.9	47.9
Velocity (ft per sec)	27.6	32.2	36.8	41.4

For water to attain a velocity of 27.6 ft per sec, a free fall of only 12 feet is necessary, neglecting air resistance. While these are obviously high velocities, they are not uncommon and appear quite often in falls and rapids (Hjulström, 1935, p. 311; he also states that the minimum velocity necessary for cavitation to occur in a stream is about 12 meters per second (39 ft per sec), but he does not give an adequate derivation or explanation of this figure).

Because there seems to be no widely accepted stream slope equation applicable to these velocities. it will be possible to give only an indication of the slope required for a velocity sufficient for cavitation. Manning's equation and the later modifications of it are not applicable, but an empirical equation derived by Ehrenberger (1926) and recently verified experimentally by Hedberg (1942), is applicable to steep slope flow. This equation holds for stream slope angles with the sine greater than 0.153 and less than 0.707 (approximately 9° to 45°). Because the equation was based on experiments on flow through an inclined flume of planed wood, the bed roughness of a natural stream introduces an error that is assumed negligible for the following approximate calculation.

By assuming appropriate dimensions for a natural stream, the velocity corresponding to the slope at the lower limit of the range of applicability of the equation may be calculated as follows:

Average width: 12 feet

Average depth: 3 feet

Hydraulic radius (r): $\dfrac{\text{cross-sectional area}}{\text{wetted perimeter}} = \dfrac{36}{18}$

Sine of slope angle (s): 0.153 (approximately 9° slope)

Mean stream velocity: v

$$v = 97\ r^{0.52}\ s^{0.40}$$

$$v = 97 \left(\frac{36}{18}\right)^{0.52} (0.153)^{0.40}$$

$$v = 65.6 \text{ ft per sec}$$

Although the channel roughness may be ignored for shooting flow (Hjulström, 1935), the curving of the stream channel would lower the velocity to some degree below the value indicated by the above calculation. The magnitude of the effect of this factor may vary widely depending upon the characteristics of each stream.

The above calculations have shown that cavitation may occur at 27.6 ft per sec at a depth of 3 feet and also that a slope of 9° is sufficient for a velocity of 65.5 ft per sec in a stream 3 feet deep by 12 feet wide. It is reasonable to expect cavitation under favorable conditions in a stream of this size with a slope somewhat greater than one-half of the 9° slope.

It should be pointed out again that many factors such as the cross-sectional velocity distribution and the amount of dissolved air have had to be neglected in the calculations because of lack of data or complexity, and often both, but they are important when one is considering the possibility of cavitation erosion at a specific point in a stream.

The mean velocity has been used in these calculations for simplicity, but cases may easily occur where there is no cavitation at the mean velocity but cavitation does occur at the maximum velocity, although calculations would indicate that cavitation erosion is unlikely. There is a velocity variation over short time intervals as well as in cross-sectional distribution in streams. Turbulence and various streamline configurations also contribute to the difference between the mean and maximum velocities. Proof of this variation is easily obtained. Since it is easy to detect the very audible noise of cavitation, sound is a better criterion than sight for the inception of cavitation especially if the occurrence is sporadic in both time and location. Intermittent cavitation noise without visible evidence is common for mean velocities slightly lower than those which calculations indicate as necessary for cavitation. Irregular variation in the noise level, which is more or less proportional to cavitation violence, also indicates the variation in velocity with time for continuous cavitation conditions. Under most conditions, the velocity fluctuation would not be great but it would be sufficient to allow some erosion at favorable locations at lower velocities than calculations suggest.

The author has been unsuccessful in attempting to find reliable data on the air content in the water of high velocity streams. In 1926, Ehrenberger published an equation relating air content of a stream flow to hydraulic radius and slope, but the result of calculations based on these formulas does not seem to be verified by observations of actual conditions. Although the air content of streams may generally be assumed low, only future data can confirm the assumption.

The shape of the erosional form caused by cavitation is highly varied. The area producing the bubbles, the length of the low-pressure area, the average bubble path, the variation in pressure with time, and the wall shape are all factors affecting the erosional form. The depth of the erosion at a given point depends statistically on the number of the bubbles collapsing at that point. The great variation in the factors mentioned above makes it evident that no standard shape can be ascribed to cavitational erosion forms.

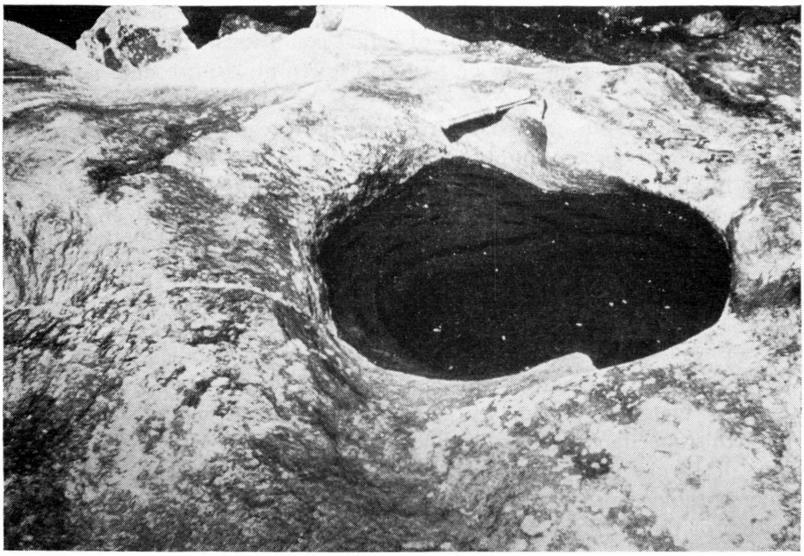
CAVITATION IN NATURE

Because cavitation erosion does not depend on the abrasive properties of transported material, erosion by glacial meltwaters is susceptible to explanation by this mechanism. The potholes found so frequently near and at the margin of former continental ice sheets may well be considered. In studies of these potholes by Elston (1917, 1918), Alexander (1932), and others, the formation of the potholes has been attributed to many mechanisms. They are found in a great variety of rock types and with many shapes and sizes up to

PLATE 2

Cavitation potholes (Mt. Tecumseh, New Hampshire)

A. Water-filled cavitation potholes. The pick handle points upstream.



B. A cavitation pothole deepened by abrasion of rotating pebbles. A shallow shelf below the pick and on the near side indicates an original shape like the lower pothole in A above. Upstream was to the right.

12 feet in diameter and 60 feet deep, as at Taylor's Falls, Minnesota. Many of the potholes cannot be related to any stream channel, yet a stream channel would need a long interval of time to erode such a volume of rock (using normal erosional mechanisms) and would have to form a stable channel leaving obvious geological evidence of its presence and continuity. The erosional mechanisms proposed by Alexander are: (1) rotary action of water with abrasive rock fragments (producing "eddy holes"); (2) direct impact of water and abrasive rock fragments (producing "gouge holes"); (3) falling water and rock fragments (producing "plunge-pool holes"). Each of these processes would not normally start a deep hole of the volume of many potholes without the action of a major stream channel over a long period.

Cavitation may well be the mechanism that started the formation of these potholes. The volume and velocity of glacial streams is often great, but they are also extremely variable in time. Because cavitation is effective under these conditions and acts very quickly, a shallow hole could form rapidly, and natural erosion by any of the processes named above could soon form a pothole. A hole in a stream bed tends to enlarge itself by trapping boulders and pebbles which are rotated by the stream and abrade the sides of the hole. The supply of rock fragments and debris must not exceed the rate of erosion in the pothole or the hole would soon be filled.

Hjulström (1935, p. 318) refers to several forms and gives a picture of one form observed near glaciers in fjords near Oslo. These forms are of the general shape which could be expected by cavitation erosion. He also refers (p. 319) to descriptions and pictures from other authors which may well be cavitational forms. The abrasion by rotation of rock fragments would destroy the cavitation shape in a short time so the forms mentioned above may well be very short-lived features under most conditions (pl. 2). To preserve the cavitation shape, the normal erosion processes, which would form a pothole, must be arrested before the transition of the principal erosional mechanism from cavitation to abrasion.

The mechanism of cavitation[1] may be applicable to hydrothermal conditions. In general, fluids not in a hydraulically closed system cannot transmit mechanical forces, but cavitation can produce mechanical force in an open system without excessive fluid velocities if the temperature is high enough to have the vapor pressure near the absolute pressure. A study of the conversion of the kinetic energy of the fluid flow to the potential energy of the phase change and back to kinetic energy again in shock waves could show how large this effect might be in hydrothermal conditions.

Cavitation might produce a fine shattering of wall rocks in hot spring areas that would aid the penetration of altering solutions; one might thus account for some of the fine fractures in some ore specimens, but cavitation would not generally be expected under these conditions. Volatiles in the fluid

[1] Although the word "cavitation," strictly speaking, postulates the same chemical composition for vapor and liquid phases, there may be a marked difference in composition between vapor and liquid in hydrothermal conditions. Because the mechanism is essentially unchanged, it will be referred to as cavitation in this paper regardless of the composition of the phases.

would tend to form permanent bubbles that would expand with decreasing pressure on approaching the surface rather than collapse violently. The gas content of these bubbles would also act like an air cushion during the collapse. Finally, the fluid would either have to flow at high velocity or be at a temperature near the boiling point. In the latter case the energy released from the bubble collapse may be insignificant.

CONCLUSION

Cavitation is probably an important geomorphological agent under specific conditions where water flows faster than 25 feet per second. Some types of potholes, especially those of glacial origin, may be started by cavitation eroding a shallow hole one to several feet in plan dimensions. The erosion takes place downstream of an irregularity in the channel where streamlines diverge from the channel sides or bottom. Later, rocks trapped in the hole may deepen and enlarge it by abrasion during rotation by the water flow.

In hydrothermal conditions, cavitation would be expected only very rarely, and evidence of its action would easily be destroyed by later alteration or replacement.

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* Note: Excellent bibliographies of references on cavitation may be found in the Symposium (1947) and in Eisenberg's paper (1950).

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